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Institute for Environment and Sustainability

# Workshop on Life Cycle Analysis and Recycling of Solar Modules - The "Waste" Challenge

## Brussels, 18-19 March 2004

# Proceedings

Edited by
Arnulf Jäger-Waldau

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## Preface

This is the record of the 1st Workshop on "Life Cycle Analysis and Recycling of Solar Modules – *The "Waste" Challenge*" held in Brussels on 18/19 March 2004. The workshop had two focus points.

First, to rise the awareness of the Photovoltaic Community about the European Directives 2002/96/EC on waste electrical and electronic equipment (WEEE) and 2002/95/EC on the restriction of the use of certain hazardous substances in electrical and electronic equipment (ROHS), which have to be implemented by the Member States in 2004. These directives will have a significant impact on the PV industry, not only because the future waste classification of PV modules is an important issue, but also the sustainability and the green image of the PV industry as a whole has to be considered.

The second focus was on Life Cycle Assessment the correct evaluation of External Costs and the Recycling of Solar Modules, which will help to avoid these problems. The workshop gave an overview about the current scientific and political discussion, identified problems and showed the way for possible solutions.

We are grateful to the invited speakers for their willingness to share their knowledge and devoting their time for this event as well as all attendees for their participation in the lively and fruitful discussions.

The content of the proceedings can also be found at the website of the Scientific Technical reference System for Renewable Energies and Energy End-Use Efficiency:
streference.jrc.cec.eu.int

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- European Commission, DG JRC, Institute for Environment and Sustainability
- Deutsche Solar AG

Ispra, March 2004

Arnulf Jäger-Waldau
European Commission, DG JRC
Institute of Environment and Sustainability, Renewable Energies Unit

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## AGENDA

**Thursday, 18 March 2004**

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| 09:00 - 09:20 | Welcome and Introduction to the Workshop<br>Arnulf Jäger-Waldau, EC DG JRC, Ispra |
| **Theme one:** | **Life Cycle Assessment** |
| 09:20 – 09:40 | *LCA in the European Environmental context*<br>Tomas Rydberg, EC DG JRC, Ispra |
| 09:40 – 10:00 | *Rethinking life cycle assessment of emerging technologies*<br>Björn Sanden, Chalmers University Gotenburg, Sweden |
| 10:00 – 10:20 | *Critical Issues in the Life Cycle Assessment of Photovoltaic Systems*<br>Erik Alsema, Utrecht University, The Netherlands |
| 10:20 – 10:50 | Coffee |
| 10:50 – 11:30 | *Life Cycle Impact Analysis of Cd in CdTe PV Modules*<br>Vasilis Fthenakis, Brookhaven National Laboratories |
| 11:30 – 12:00 | Discussion |
| **Theme two:** | **PV System Performance and External Costs** |
| 12:00 – 12:20 | *20 years module testing – Lessons learned*<br>Tony Sample, EC DG JRC, Ispra |
| 12:20 – 14:00 | Lunch |
| 14:00 – 14:20 | *Performance of PV systems under real conditions*<br>Thomas Nordmann, TNC Consulting AG, Erlenbach, Switzerland |
| 14:20 – 14:40 | *External Cost of PV: what is it based on*<br>Mariska de Wild, ECN, The Netherlands |
| 14:40 –15:00 | *The 'ExternE' methodology to assess external costs of energy conversion and some results on the external costs of PV and other electricity generating techniques*<br>Rainer Friedrich, University Stuttgart, Germany |
| 15:00 –15:30 | Discussion |
| 15:30 – 16:00 | Coffee |
| **Theme three:** | **Recycling** |
| 16:00 – 16:20 | *Recycling of silicon solar cells and modules*<br>Karsten Wambach, Deutsche Solar, Germany |
| 16:20 – 16:40 | *Compound semiconductor solar cell recycling*<br>Niels Warburg, Universität Stuttgart, Germany |
| 16:40 – 17:00 | *Recycling of compound semiconductor modules*<br>Rainer Gegenwart; First Solar |

**Friday, 19 March 2004**

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|---|---|
| 09:00 – 09:20 | *Wet Processing and Recycling of Compound Semiconductor Cells*<br>Lutz Giese, Bundesanstalt für Materialforschung und -prüfung (BAM) Berlin, Germany |
| 09:20 – 09:40 | *Recycling PV Modules in the US*<br>Ken Zweibel, NREL, USA |
| 09:40 – 10:00 | Discussion |
| 10:00 – 10:20 | Coffee |
| **Theme four:** | **Waste Policy** |
| 10:20 – 10:50 | *EU waste directives and their consequences for PV*<br>Arnulf Jäger-Waldau, EC DG JRC, Ispra |
| 10:50 – 11:20 | *Regulation scenarios of waste PV-module management*<br>Stéphanie Zangl, Ökopol, Hamburg, Germany |
| 11:20 – 11:50 | *The EU Waste Directives and their consequences for European PV industry*<br>Eleni Despotou, EPIA, Bussels |
| 11:50 – 12:10 | Discussion |
| 12:10 – 12:30 | Workshop Summary, Conclusions |

# Executive Summary

The European Directives 2002/96/EC on waste electrical and electronic equipment (WEEE) and 2002/95/EC on the restriction of the use of certain hazardous substances in electrical and electronic equipment (ROHS) have to be implemented by the Member States in 2004 and will have a significant impact on the PV industry in the long term. Not only the future waste classification of PV modules is an important issue, but also the sustainability and the green image of the PV industry as a whole has to be considered.

Life Cycle Assessment (LCA), the correct evaluation of External Costs and the Recycling of Solar Modules will help to avoid these problems. The aim of this workshop was to give an overview about the current scientific and political discussion, identify problems and discuss possible solutions.

About 40 participants attended, including the major players from European industry. Of particular note was that the CEO and the Vice President of the largest Cadmium Telluride Manufacturer in the US (First Solar LLC) participated as well as specialists from the US Department of Energy, the Brookhaven National Laboratories and NREL. Colleagues from DG TREN and DG RTD were present and input was received from DG ENV, although they could not be present.

During the workshop 16 presentations were given, covering the topics LCA, reliability and external costs, recycling technologies and policy regulations and impact. The opening key-note presentation was given by Tomas Rydberg from the IES Soil & Waste Unit, outlining the importance of LCA in the European Environmental Policy Context.

LCA is a very useful tool to be used for the optimisation of the production. However, B. Sanden pointed out that if LCA is used to compare the environmental impact and the external costs of different energy generation systems one has to keep in mind the question to be answered and that the results are only valid within the model and its assumptions. For PV the question could be either:

- How large are the life-cycle emissions of greenhouse gases (GHG) ($CO_2$) from a PV-panel (per 1 Wp)?

or:

- How does the investment in a PV-panel (per 1 Wp) effect GHGs ($CO_2$)?

The first of these questions is state-oriented and more accounting, whereas the second question is change-oriented and looks at the effects of change. Especially for emerging technologies like PV, future states with high technology penetration are more relevant than current or historic situations. Different time horizons and scale of technology implementation influences the choice of methodology if one tries to assess possible future effects. Therefore, the learning curves of technologies and the potential to solve a given problem have to be made visible, i.e. quantified. If this effect is not taken into account, there is a risk that society will invest too little in advanced technologies with short-term drawbacks, ignoring the huge long-term advantages.

The next two presentations dealt with more technical questions related to the different cell technologies. Energy pay-back time, i.e. the time needed for the PV modules to generate the same electricity, which was used to fabricate them, is often quoted as a pro or con argument depending on the individual background. First of all, it is important to note, that only Renewable Energy systems (excluding biomass) have a positive energy pay-back time, i.e. the systems generate more electricity during their lifetime than was used for their production. All other energy resources have a negative balance. Second, if we look at the energy pay-back time of PV modules, we have to take into account that the photovoltaic industry is not yet a mature one and that a lot of production processes have to and will be optimised if the industry continues to grow with the current 30 to 40% per annum and economy of scale becomes more important. In addition, it has to be taken into account whether PV has only a single function, i.e. electricity generation, or when used in building-integrated concepts forms a part of the building shell itself, serves as a shading element or has some additional features like sound barriers, thermal insulation etc. There is a lack of modern LCA data of recently established large PV productions and uses that should be updated as soon as possible.

Nevertheless, PV-Systems are industrial products and their production has an environmental impact. When talking about environmental impacts, the total material flows and energy needs have to be considered. A remarkable example is the case of cadmium. Cadmium is a by-product of zinc mining and has to be considered as toxic waste. If it is now used to manufacture CdTe solar cells, and the modules are used in a controlled environment like a central power generation facility, this use can be considered as “safe” cadmium sequestration. Such use of Cd is about 2500 times more efficient than using Cd in NiCd batteries, as measured by the energy output of the products. The difficulty of effectively collecting “end-of-life” CdTe PV modules from dispersed operations was discussed. Collection and recycling programs were outlined in separate presentations by Gegenwart, Zweible, and Fthenakis, which could effectively facilitate such collection and recycling. . Another aspect is the fact that the normal operation of a coal-fired power plant produces a minimum of about 2 to 7 g Cd/GWh air emissions[1], under the assumption, that 98.6% of Cd emissions are captured with electrostatic precipitators or filters. or CdTe PV, in the most likely case, emissions from the whole life-cycle of the modules total only 19 mg Cd/GWh air emissions, i.e. 100 to 360 times lower than those from coal fired plants, which CdTe solar cells could replace.

The often-quoted safety risk of CdTe modules in a fire makes the assumption that all the cadmium present in the module gets evaporated in the course of the fire. Recent comprehensive experiments proved that the current generation of glass-glass CdTe modules on the market do not have this safety risk due to the fact that in the case of fire with temperatures between 760 and 1100ºC, only 0.5±0.1 wt.% of the cadmium content of the modules was released. This release rate was measured by heating small (1.5-in by 12-in) pieces. It was estimated that Cd emissions from whole modules should be 13.5 times lower (i.e., 0.04%). The experiments showed that the cadmium diffuses into the glass and is kept there, and if emissions occur those will be extremely small.

The actual lifetime of a product and its performance and reliability under real working conditions is important for the assessment of External Costs and future waste amounts. The results of the last 20 years of module testing at the Joint Research Centre in Ispra revealed that the lifetime of current PV modules is well above 20 years and even lifetimes of more than 30 years can be expected. Most of the failure mechanisms during the tests are in the meantime understood and give the manufacturers valuable feedback for the improvement of their products. Long term (20 years) outdoor testing showed that despite visual impact, e.g. yellowing, the electrical performance is still alright. Therefore, client acceptance might be more influenced by optical appearance than actual technical performance.

The International Energy Agencies PVPS Task 2 collected information on the technical performance, reliability and cost of PV systems located in 15 countries. Comparing early PV installations (1991-1994) and new installations (after 1996) in Germany, a significant rise in the mean annual performance ratio (PR) of 13% was found. The high level of average PR (0.74) and nearly constant annual PR values during five operational years (1998-2002) indicate that the quality of the newer systems in Germany has significantly increased. Similar results were gained from the 334 investigated grid-connected PV systems in 11 other countries.

Rainer Friedrich presented the methodology and some results of the ExternE project (funded by DG RTD). The *Impact Pathway Approach* is seen as the state-of-the-art methodology for quantifying environmental external costs from energy conversion. The methodology is being continuously improved and extended. Thus, according to the version of the methodology used, different results will occur. After the presentation a heated discussion started about some results of the ExternE study and the impact of the DG RTD 2003 publication. The main criticisms were that:

- An emerging technology is compared by using the data from of one PV system monitored for only one year with data on established (optimized) technologies.
- The database used for the 2003 publication is based on estimated PV production data from a pilot plant of the late 1980s, which is completely outdated.
- The system evaluated was monitored only for one year and not for two years as required by the European Guidelines for PV system monitoring[1]
- The methodology developed and used in the ExternE study does not take into account the fact that conventional energies have a resource demand (fuel) during operation, whereas some RE like wind and PV do not. The ExternE methodology has no tool to include credits for risk avoidance and does not price all the risk of conventional energies, e.g. resource depletion, security costs, proliferation of nuclear weapons, conflict potential, waste storage.

But on the other hand it was acknowledged that the development of the methodology for the determination of external costs was successful to establish a very useful tool for policy support. It was pointed out that the results are and will remain uncertain (location, technologies used, willingness to pay, …) but that the quantification of external costs has also reduced the uncertainty about impacts of technologies and measures as a whole. In addition, there was agreement that for such kind of evaluations the approach, the methodology as well as the calculations need a rigorous and peer review. Meanwhile Brookhaven National Laboratory offered their support to supply data to update the ExternE study and compare the result with other studies.

The following session dealt with the technical problems of recycling of solar modules. First recycling solutions are in a pilot plant state at present. Deutsche Solar AG put the first thermal

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[1] Guidelines for the Assessment of Photovoltaic Plants, EUR 16338 EN, EUR 16339 EN and EUR 16340 EN, 1995

recycling line dedicated to PV modules of any technology and manufacturers in operation recently. With respect to increasing waste amounts from production, transportation or installation and from field installations of PV generators the capacity of the pilot plant is sufficient to recycle the collectable end-of-life modules in Europe at present. Running several lines today will therefore not be cost effective. The recycling process of First Solar's pilot plant in USA is dedicated to CdTe modules of their own production, but the concept could be licensed if need arose.

The costs of waste treatment are generally included in the costs of all components in the value chain but not yet for modules at the end of their life. These module waste costs can be calculated between 0.10 €/Wp and 0.40 €/Wp depending on type of module, transportation waste treatment and disposal costs. Modules with crystalline silicon solar cells benefit from successful recovery of wafers to cover at least parts of the end-of-life costs, but thin film modules may suffer from the low value of the separated products. The energy consumption using a reclaimed wafer is about 20 – 30% compared to a new wafer in a module thanks to avoidance of new crystallisation and cutting.

The European SENSE project, funded by the EU in the 5th Framework Programme, uses the approach of Life Cycle Engineering (LCE) to analyse thin-film solar cells, to support the development of recycling processes and to optimise solar cells.

In 2002, the German Federal Material Reference Centre (BAM) conducted studies on the abilities (i) how to monitor large-scale electronic waste streams and (ii) how to recycle photovoltaic thin-film modules (CdTe and CIS technology) by wet mechanical processing. It is assumed that environmental compatibility can be improved by processing applying existing wet-mechanical technology. Environmentally friendly technologies such as photovoltaics have to strictly observe the rules of sustainability to meet requirements by public opinion and environmental compatibility. Whereas until the middle of the 21st century the expected waste quantity from photovoltaics may not reach today's quantities of main waste material currents, nevertheless the development of the market and expected waste quantities should be investigated carefully. Recycling must be aimed at preventing environmental risks and furthermore resource shortages. Taking this into account, disposal and downcycling strategies have to be rejected. A real aim to achieve should be material recycling within an integrated recycling. The processes applied to recycle the modules have to be evaluated carefully in order to assess the ecological effects like it will be done in the integrated 6th Framework Project Crystal Clear. Nevertheless, it has to be taken into account that socio-economic sustainability contains both ecological as well as economical sustainability.

To get the international picture, experts from the US and Japan were invited. In the US no Federal actions are implemented, except for general requirements such as RCRA (hazardous waste definitions). Some States have regulations that might go beyond RCRA, e.g. California (CA) has other limits for hazardous materials and North Carolina and perhaps CA may have recycling programmes for items with cathode ray tubes. In general, few US PV companies have any policies, with a notable exception (First Solar) and some awareness of lead solder issues by traditional silicon wafer companies.

The reasons for this are small volume of products and even smaller volumes of waste (given long outdoor life of modules, which postpones disposal) as well as the tiny amounts of problematic materials (lead solder, and some special elements in newer, barely commercial technologies like selenium, cadmium). In addition, PV is seen as a new industry with much potential value, but which needs time to get established before regulations make a deep impact on key technical choices.

- What if short-term priorities kill off the best, new choice(s) before they get started?
- How sure are we that we have the proper balance of good/bad in our evaluations – e.g., does CdTe get a *credit* for sequestering waste Cd from zinc mining? How about improved energy-payback for thin films?

"Regulation Scenarios Waste PV Modules" discussed the question how the European Waste Directives would directly influence the PV Business. Due to the long life-time of the PV modules, the yearly emergence of PV modules that need to be disposed reaches the same dimension as the installed capacity with a delay of about 30 years. Therefore, the expected generated waste amounts for 2002 in Germany was of approximately 290 t, for 2010 it will be of about 1,110 t and for 2040 it is expected to be of 33.5 thousand tons according to the Oecopol-study.

A self-binding commitment of the industry would allow utilising the economic incentive of silicon-recycling. The necessity to ensure clearly-defined, revisable and ambitious goals as well as an efficient monitoring has to be pointed out. However, facing the long life-time of the modules and the high dynamic of the market, a fundamental problem of this solution is that some of the producers may not be operating on the market any more at the equipment's "end-of-life-time". A solution could be the pre-financing of the anticipated module returns and recycling costs with annuities issued by international insurance companies.

EPIA pointed out that even today module recycling is possible via an existing voluntary take-back system from manufacturers and distribution partners and an operating recycling plant in Europe.

# Conclusions

PV modules today are known as very stable and reliable products. The average lifetime is estimated to be more than 25 years. Despite this, an increasing number of end-of-life modules and rejects from production can be observed all around the world. At present defect modules can already be recycled or disposed at special landfill sites at rather low costs without problems since they are very resistant to environmental attack. The latter is frequently not acceptable for end users who demand the re-use and recycling of the defect PV products. Several companies and research institutes world-wide have been working on technologies for recycling crystalline silicon solar cells and thin film modules though the amount of waste is at least 3 orders of magnitude less compared to other electronic equipment.

The workshop presentations gave an overview about the current scientific and political discussion in Europe and the US. Some issues, like the use of external cost figures were lively and controversially discussed and led to the conclusions, that the Photovoltaic Community has to be more proactive in this kind of activity as well. The workshop fulfilled its goal to create awareness amongst the Photovoltaic Community about the image and economic problems, which might arise when recycling is not addressed properly. The following conclusions can be made:

- The PV industry already has a high sensibility towards the acceptance as a green and sustainable energy source. Therefore, the PV community acts pro-actively towards possible problems for the PV industry concerning waste.
- PV is not a classic *'throw away'* consumer item. Therefore, PV products should be compared to energy industry products and not consumer items.
- For the Energy Systems Assessment, the "*Life Cycle Energy Requirement Balance*" was suggested as an indicator.
- For emerging technologies like Photovoltaics, future states with high technology penetration are more relevant than current or historic situations. Different time horizons and scale of technology implementation affect the choice of methodology if one tries to assess possible future effects. Therefore, Life Cycle Assessment for Photovoltaics should be change oriented, otherwise there is a risk that society will invests too little in advanced technologies with short-term drawbacks but huge long-term advantages.
- The database for the calculation of external costs of photovoltaics is still very uncertain due to the limited key production figures available to calculate the risks of current products, respectively predict it for future module generations. More work has to be done to generate this database. For silicon-based modules this will be done in the framework of the recently started EU FP6 Integrated Project "*Crystal Clear*". So far credits for resource preservation and risk avoidance are missing in all external cost models.

- The industry representatives present agreed to a Technical Working Group and set it up to elaborate technical issues in view of the review of updating procedures of the Waste Directive. The work will be co-ordinated by EPIA.
- Consensus to have a follow-up in the Autumn to discuss the results of the WG and the recent developments in view of the deadline of 13 February 2005 for the review on the Electrical and Electronic Waste Directive and the Hazardous Waste Directive.
- The Photovoltaics Industry and the Research Community need to establish a unified political strategy, which allows for the future development and implementation of PV as a green and sustainable energy.

We have to keep in mind that according to the IEA Energy Investment Outlook 2003[3] the world will need to invest 16 trillion $ over the next three decades to maintain and expand the energy supply. The largest share, 10 trillion $ will be needed for the electricity sector. The European Union has to invest about 1.6 trillion € up to 2030, just to replace old energy generating capacities. The life-time of such energy generating capacities is in the order of 40 years, i.e. if we want to have a diversified, secure and risk minimised energy system with reduced $CO_2$ emissions by 2050, a large share of renewable energies is absolutely necessary and the decision to install it has to be made now. For these decisions, photovoltaics has to be compared to the traditional energy sector, and one has to ask the following questions:

- PV replaces other sources of energy that themselves cause pollution. Where is the implied credit for PV?
- PV does not consume electricity, it *produces* it.

At the end I would like to quote our colleague Ken Zweibel from NREL, who in his presentation already gave the conclusion of this workshop:

*"Our goal should be to smartly facilitate the use of Photovoltaic modules, including proper recycling when the industry reaches a more stable, mature level – and always avoid imposing technology choices prior to proper knowledge of tradeoffs and potentials. The risks of reducing Photovoltaic module competition and reducing long-term cost viability of Photovoltaics for energy significance would be otherwise too great."*

[3] World Energy Investment Outlook 2003, IEA/OECD, Paris 2003

# Life Cycle Assessment (LCA) in the European Environmental (Policy) Context

Tomas Rydberg[4]

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## *Abstract*

The European Community's 6th Environmental Action Programme calls for more sustainable use of resources, waste prevention, and recycling - aiming at minimising environmental impacts associated with waste generation and resource use, while promoting economic growth and an improved quality of life. In this context, Life Cycle Assessment (LCA) is increasingly seen as a vital tool for supporting product- and waste-related policies in the EU. Existing policies and directives that address the treatment of waste include "The Waste Framework Directive, WFD" (Council directive 75/442/EEC of 15 July 1975 on Waste), with subsequent amendments, and the "Landfill Directive" (Council Directive 99/31/EC of 26 April 1999). Other directives address specific product groups or waste streams. Directives which are strongly relevant to the topic of this workshop are The "RoHS" directive[5] and The "WEEE" Directive[6]. These are designed to tackle the fast increasing waste stream of electrical and electronic equipment and complement European Union measures on landfill and incineration of waste. Directive 2002/95/EC requires the substitution of various heavy metals (lead, mecury, cadmium, and hexavalent chromium) and brominated flame retardants (polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE)) in new electrical and electronic equipment put on the market from 1 July 2006. This prevents the generation of hazardous waste. The WEEE directive describes targets concerning the recovery and recycling of WEEE, targets which have to be met by 31 December 2006. The recycling targets range from 50 to 80%, depending on the type of equipment, and recovery rates are also set for the different types of equipment. The WEEE directive also makes producer responsibility mandatory.

Complimentary measures and instruments are now helping address waste management and increase efficient use of resources from a more holistic perspective. These rely on life cycle thinking and associated assessment tools – considering the upstream and the downstream affects of providing goods and services. The Integrated Product Policy (COM 2003:302, 18 July 2003) is a key policy in this respect, as it seeks to encourage the efficient use of resources and the prevention of wastes by promoting life cycle thinking and life cycle assessments through product-orientated measures and instruments. The life cycle approach is also a central theme in the recent EU communications towards waste prevention and recycling (COM

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[4] Presented at The Workshop on Life Cycle Analysis and Recycling of Solar Modules - The "Waste" Challenge, 18 and 19 March 2004. The views expressed are purely those of the writer and may not in any circumstances be regarded as stating an official position of the European Commission.

[5] Directive 2002/95/EC on the restriction of the use of certain hazardous substances in electrical and electronic equipment

[6] Directive 2002/96/EC on waste electrical and electronic equipment

2003:301, 27.5.2003) and the communication towards sustainable use of resources (COM 2003:572, 1.10.2003).

More explicit examples of the use of LCA in policies are currently less apparent. But there are a few examples worth mentioning, where LCA or elements of LCA may play a role:

The "EuP Directive" [7] is aiming at putting requirements on manufacturers and importers to the EU market to record and improve the environmental performance of their products put on the market. It is suggested that manufacturers and importers "shall perform an assessment of the environmental aspects of a representative EuP model throughout its lifecycle". Thus, although the directive does not require an LCA to be performed (and in fact in an explanatory memorandum it is stated explicitly that the requested assessment is not an LCA), elements which are normally used in LCA will be useful also in the EuP environmental performance assessment.

The "Packaging and Packaging Waste directive, PWD" (94/62/EC) has been implemented in most EU member states through producer responsibility schemes in the form of legally binding directives for recycling and recovery targets. As this and similar directives [8] are traditional in the sense that they address only the waste issue in the post-user phase and not are based on LCA study results, they have been sometimes criticised for not taking into account the issue of potential problem transfers from one environmental problem to another. In the PWD, there is a reference to LCA, stating that "life-cycle assessments should be completed as soon as possible to justify a clear hierarchy between reusable, recyclable and recoverable packaging" (OJ, 1994). In the process of updating the targets in the PWD, the European Commission recently called for a Cost-Benefit Analysis (CBA) to evaluate existing schemes. LCA was explicitly used to evaluate the environmental impacts and benefits of various schemes and scenarios.

The Commission is taking action in a number of ways to support the take-up of the life cycle thinking in society. This includes several coordination initiatives aiming at making life cycle information and interpretative tools available, as well as pilot exercises for selected products. It also includes support of research through JRC activities and co-financed projects within FP5 and FP6 projects, Life-Environment, eContent and others.

[7] "Proposal for a Directive of The European Parliament and of The Council on establishing a framework for Eco-design requirements for Energy-Using Products and amending Council Directive 92/42/EEC" (COM 2003:453, 01.08.2003))

[8] Notably "the ELV directive" (Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of-life vehicles, OJ L 269, 21.10.2000, p. 134) and the WEEE directive (The directive 2002/96/EC on Waste Electrical and Electronic Equipment, OJ L 37, 13.2.2003, p. 24.

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# Life Cycle Assessment in the European Environmental Policy Context


*Tomas Rydberg*
*Institute of Environment & Sustainability, Soil & Waste Unit*

http://ies.jrc.cec.eu.int





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## Content

- Life Cycle Assessment - basics
- LCA and Life Cycle Thinking in EU Policies

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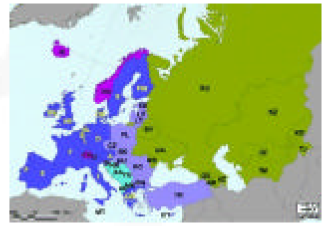
# Example Facts & Figures “The Drivers”



- Countries: 6 (1952), 15 (1995), 25 (2004)
- Population: » 450 million people (2004 -)
- World’s biggest trading block partner (19% exports, 1998)

- Waste – 2 billion tonnes/year, 10% increase per year
- Energy reliance - 70% imported by 2030, if nothing done
- $CO_2$ Emissions – 8% emissions cut by 2008-2012 under the Kyoto Protocol
- Vehicle impacts – 1 in 3 accident in life time and 40,000 deaths/year



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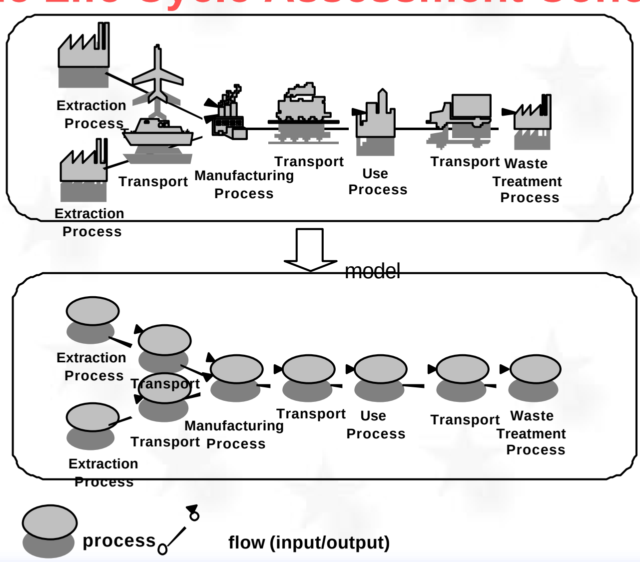
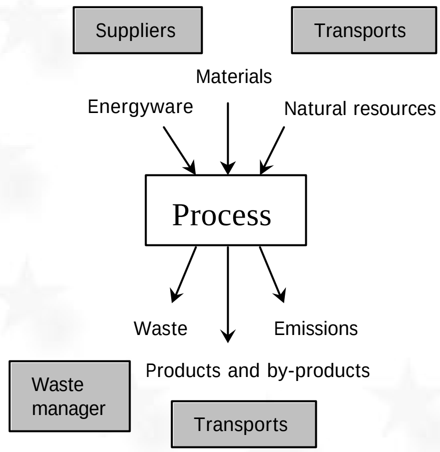
# The Life Cycle Assessment Concept



# Process – the 'building block'



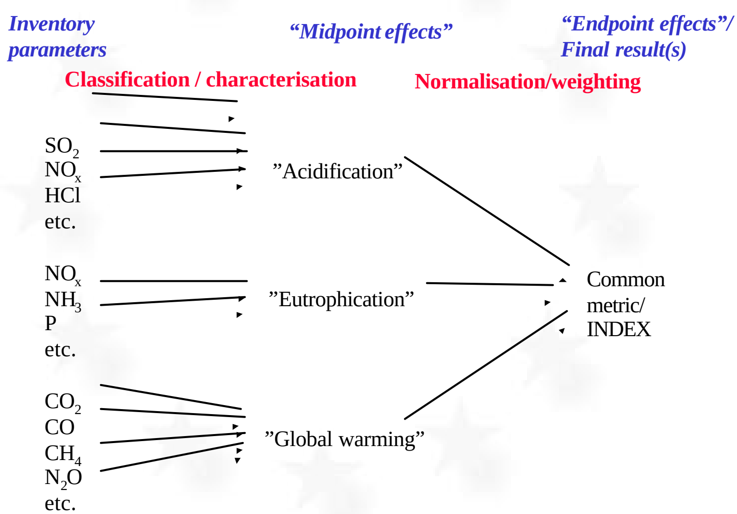

Inputs & Outputs related to

<u>unit function</u>





# LC Impact assessment



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# LC Impact assessment

## characteristic elements of some LCIA methodologies

| Method [1] | Geographical scope [2] | Indicator basis (Impact modelling depth) | | Weighting basis | | |
|---|---|---|---|---|---|---|
| | | to midpoint | to endpoint | Distance to target | Expert panel | Monetisation |
| Eco-scarcity | Switzerland | partly | | X | | |
| EPS | World | | X | | | X |
| Eco-indicator | Europe | | X | | X | |
| EDIP | Denmark | X | | X | | |
| LIME | Japan | | X | | | X |



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# Life Cycle Thinking and Policy Relationship (1)

- **Pertinent strategy and policy examples**

  - Strategy for prevention and recycling of waste
  - Strategy for sustainable use of natural resources
  - Integrated Product Policy Communication (*building on life cycle thinking*)

  - Strategic Environmental Assessment Directive (2001/42/EC) –*plans/programs*
  - Environmental Impact Assessment Directive (1997/11/EC) – *projects*
  - Impact Assessment Communication *(COM(2002) 276) – major EU initiatives*

# Integrated Product Policy

**COM 2003:302**

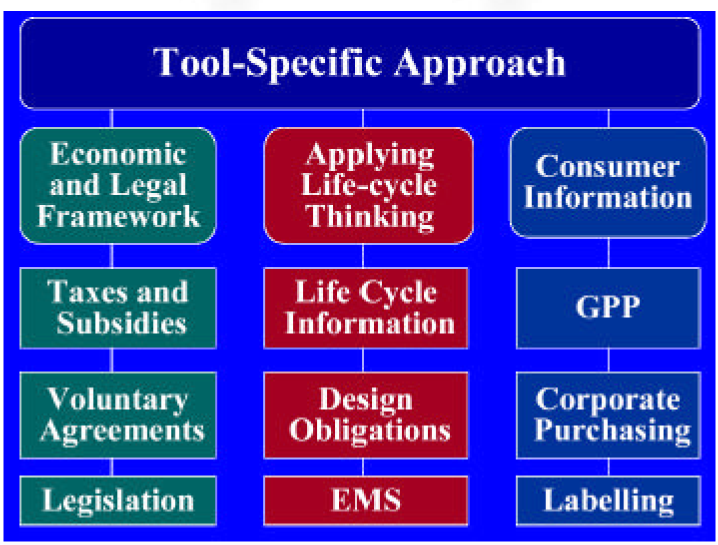
- Overarching objectives
  - How are we progressing in Policy Integration
  - What positive effects on the Environment have been achieved
- Two main approaches
  - Tool-specific approach
  - Product-specific approach







# Integrated Product Policy (1)




Source: K.K., DG ENV

# Integrated Product Policy (2)

**Product-Specific Approach**

Products with Greatest Potential for Environmental Improvement

List of products to address

↓

Tackle identified products, building on methods in the pilot products exercise.

Source: K.K., DG ENV







# Integrated product Policy (3)

## Life Cycle Information

- Directory of LCA databases
- Platform to facilitate the communication and exchange of life-cycle data (organisational and / or technical)
- Co-ordination initiative for Life-Cycle Data
- Handbook on best practice in LCA use and interpretation

Currently being investigated or/and implemented through studies, workshops and other in-house and EC/MS activities

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# Life Cycle Thinking and Policy Relationship (2)

## Specific policy examples

- **WEEE Directive (2002/96/EC)** and ELV Directive (2000/53/EC) – Extended producer responsibility / life cycle thinking (?)
- **Eco-design requirements for energy using products Directive (COM(2003) 453)**
- Packaging waste Directive (revision of 1994/62/EC) – life cycle based C/B analysis
- Sewage Sludge Directive (revision of 1986/278/EEC)
- Chemicals Policy/REACH (COM(2003) 644) – Role in regulatory risk management (?)





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# Eco-Design Requirements for Energy Using Products - Extracts (1)

"The **ecological profile is a description of the significant environmental aspects of the product throughout its life cycle, expressed in terms of measurable inputs and outputs**."

"In order to establish the ecological profile it is **not obligatory to make a life cycle analysis** (LCA) according to relevant international standards; such an obligation could create a disproportionate financial and human resources burden on enterprises, in particular SMEs. … **Whenever data from LCAs are available and can contribute to the creation of the ecological profile, they could be used**."

"this **evaluation must be done in such a way that it can reasonably be implemented by companies without incurring excessive expenditure**"

"In particular the assessment of the actual impact on the environment which is an integral part of the ISO 14040 standards' series, has a **number of limitations** (spatial and temporal differentiation of environmental processes and ecosystems, absence of linear response between system loading and the environment, different underlying values and principles of parties, leading to different formulation of environmental issues and interpretation of results) "

# Eco-Design Requirements for Energy Using Products - Extracts (2)

"1. Manufacturers of EuP **shall perform an assessment of the environmental aspects** of a representative EuP model **throughout its lifecycle**, based upon the realistic assumptions about normal conditions and for the purposes of use.

On the basis of this assessment manufacturers will **establish the ecological profile** of a representative EuP model. It shall be based on environmentally relevant product characteristics and inputs/outputs occurring throughout the product life cycle expressed in physical quantities that can be measured.

The assessment shall concentrate on and give priority to those factors, which are capable of being influenced in a substantial manner through product design."

"(j) Amounts of waste generated and amounts of hazardous waste generated

(k) Emissions to air (greenhouse gases, acidifying agents, volatile organic compounds, ozone depleting substances, persistent organic pollutants, heavy metals, fine particulate and suspended particulate matter) without prejudice to Directive 97/68/EC relating to measures against the emission of gaseous and particulate pollutants from internal combustion engines to be installed in non-road mobile machinery

(l) Emissions to water (heavy metals, substances with an adverse effect on the oxygen balance, persistent organic pollutants)

(m) Emissions to soil (especially leakage and spills of dangerous substances during usage phase of products, and the potential for leaching upon disposal as waste)"





# LCA in EC Funded Projects

(non-exhaustive list)

| Project | Description/Objective | Program |
|---|---|---|
| DANTES | Demonstrate and Assess New Tools for Environmental Sustainability: Life Cycle Assessment (LCA), Environmental Risk Assessment (ERA) and Life Cycle Cost (LCC) | Life2002 |
| CASCADE | Co-operation and standards for life cycle assessment in Europe: Accessibility, comparability and quality assurance of data used in LCA of products and the integration of LCA in the design process. | FP5: Growth |
| ECLIPSE | **Environmental and eCological Life cycle Inventories for present and future Power Systems in Europe** | **FP5: EESD** |
| e-LCA | WEB site and DBs for the adoption of IPP by SMEs) | e-Content |
| | Introduction and Implementation of Life Cycle Assessment Methodology in Estonia: Effects of Oil Shale Electricity on the Environmental Performance of Products | Life2003 |
| LCA-IWM | The Use of Life Cycle Assessment Tools for the Development of Integrated Waste Management Strategies for Cities and Regions with Rapid Growing Economies | FP5: EESD |
| Omniitox | Operational Models and Information tools for Industrial applications of eco/toxicological impact assessments: Life Cycle Impact Assessment Methods and Data | FP5: Growth |

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# Thank you !

Further info

JRC home pages: http://www.jrc.cec.eu.int
Europa web site: http://europa.eu.int

tomas.rydberg@jrc.it

# Rethinking life-cycle assessment of emerging technologies

Björn A. Sandén,

Environmental Systems Analysis, Chalmers University of Technology
Email: bjorn.sanden@esa.chalmers.se

Standard LCA methodology is developed to answer questions about environmental impacts of the current (or historical) production and use of one unit of a product or of minor product or process changes. When this methodology is used to provide answers to questions about strategic technological choices, i.e. not decisions that aim at optimising a process in an existing technological environment but decisions with the long-term goal of changing large-scale technological systems, the result is of little value and in the worst case interpretations of the result may be grossly misleading. This observation is of particular importance for assessments of greenhouse gas (GHG) emissions resulting from emerging energy technologies.

Recent LCA literature makes a distinction between two types of LCA. The terminology and exact definitions vary but I will here use the terms state- and change-oriented LCA. State-oriented LCAs answer questions of what a product or group of products can be made responsible for. Change-oriented LCAs tries to estimate effects of change on the margin. For example: How will an additional PV-plant affect emissions of greenhouse gases?

State-oriented LCA traditionally looks backward and use average or plant specific data. Some proponents of change-oriented LCA would argue that state-oriented LCAs should not be used for decision support at all, but only for accounting. I think state-oriented LCAs could be useful for strategic decision support, but it is critical to analyse a relevant state.

Local emissions of GHG add to a global stock: there are no correlation between the localisation of GHG emissions and climatic effects, and GHG emissions does not primarily lead to an instant problem but builds up a problem of climatic change over time. The cumulative emissions over the next century, and not the current emissions, are the main cause of concern. In addition, PV electricity currently supplies about 0.01 % of world electricity demand and 0.001% of world primary energy demand. The GHG effect of current PV systems is therefore of almost no relevance. Instead, relevant states would be future states with large fractions of PV in the energy system. This implies that a relevant state-oriented assessment needs to take into account the time and scale dependence of a number of parameters.

The most obvious time and scale dependent factor is technical development that could lead to *product and process improvements* and also to *radically new technical combinations*. Two other factors are of at least equal importance. First, the most important *background systems* in LCAs, electricity and transport supply, are dependent on time and in the some cases also on the scale of adoption of a technology. Regardless of what happens to PV, it is likely that the electricity mix will change over the next couple of decades. But even more importantly, a large-scale penetration of PV will make the electricity system less carbon intensive, and thereby decrease the amount of carbon dioxide emissions needed to produce PV modules with average electricity. Methodologically this can be handled by using scenarios of PV-penetration or changing the system boundary so that used electricity is deducted from produced electricity. Second, an increased scale of production will also change the environmental burden stemming from inputs currently derived from *limited resource flows*. For PV this is of particular importance for technologies using rare and minor metals indium, tellurium and ruthenium.

The change-oriented approach to LCA claims to investigate the implications of a choice, for example the choice to invest in more PV production. In this type of studies marginal data is often used. Therefore, change-oriented LCAs are not additive like the state-oriented. This line of thinking brings in scale considerations and price effects into LCA. In state-oriented LCAs, the supply of inputs is regarded to be elastic: If I demand one more unit of A (electricity from hydropower), one more unit of A will be produced. But if the production of A (hydropower) cannot increase (inelastic supply), B (electricity from coal power) will increase instead. Another example of inelastic supply is minor metals. Since cadmium mining is inelastic (dependent on zinc demand), more cadmium demand for production of solar cells does not have to lead to more cadmium extraction but instead to increased cadmium prices and less cadmium use in other applications. Similarly, in standard LCA, demand for the assessed product is regarded to be *inelastic*. But, an additional PV-plant could affect electricity prices and therefore also electricity consumption at the margin. In conclusion, change-oriented LCA has started to use marginal and equilibrium thinking and take into account some supply and demand relationships and short term reversible price effects, ideas stemming from neoclassical economics.

But not all effects of a decision are reversible and restrained by negative feedback mechanisms to maintain some kind of equilibrium. There are also positive feedback mechanisms leading to cumulative effects. An increased use and production of PV would add to stocks such as fixed capital, knowledge and advocates and effect structures with great inertia such as networks, institutions and attitudes. Without these cumulative effects the high PV penetration rates that really could have an impact on GHG emissions, can never be reached. Many of the cumulative effects cannot be quantified, but the learning effect of increased adoption of PV can be quantified in terms of cost reductions by using an experience curve. An investment in learning in a technology could be given a carbon dioxide credit in proportion to its potential to substitute fossil fuels and to the investment's share of the total investment needed to make the technology economically competitive with the fossil fuels. In this way the main environmental reason for investing in a technology like PV is also acknowledged in LCAs, that is, learning for large-scale change in the long term. If this effect is not taken into account in change-oriented LCAs there is a risk that society invests to little in advanced technologies with short-term drawbacks but huge long-term advantages. To make a calculation that takes into account learning effects, again a number of choices have to be made. How large is the potential of PV? How fast can it diffuse? What is the business-as-usual scenario? To keep it simple, mitigating climatic change is mainly an issue of developing a substitute for coal. Solar energy is one of few alternatives that can take that role. An upper bound of the learning effect could then estimated from the potential to avoid emissions from 100 000 EJ of coal over the next 200 years. The result is stunning. The learning CO2-credit of a PV installation in 2004 can be estimated at 200 000 kg/Wp, which can be compared to avoided emissions during operation of 20-40 kg/Wp, and emissions from the production of modules and arrays of up to 4 kg/Wp (if all energy used is assumed to be derived from coal). Even if the coal substitution potential is reduced by a factor of 1000, the learning effect, as estimated here, totally dominates the impact on GHG emissions resulting from a PV investment today.

# Rethinking life-cycle assessment of emerging technologies

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**Environmental systems analysis**
Chalmers University of technology
Göteborg, Sweden






The first thing to think about in LCA

## What is the question?

If the answer is **42**…

You need to know the purpose and understand the methodology to be able interpret the answer

”The hitch hiker’s guide to LCA”
Baumann and Tillman 2004

# What is the question?

LCA methodology needs to be adapted to the type of question it tries to answer

Standard LCA methodology

The current production and use of one unit of a product or minor product or process changes.

Strategic technology choice.



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# What is the question?

LCA methodology needs to be adapted to the type of question it tries to answer

Standard LCA methodology

The current production and use of one unit of a product or minor product or process changes.

Strategic technology choice.

**Interpretations of the result may be grossly misleading.**

LCA and recycling of solar modules, Brussels, March 18-19 2004

How large are the life-cycle emissions of greenhouse gases (GHG) ($CO_2$) from a PV-panel (1 Wp)?

How does the investment in a PV-panel (1 Wp) effect GHG ($CO_2$)?





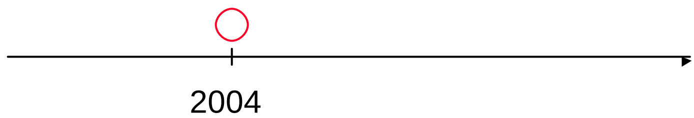
# Two types of LCA

- State-oriented (accounting)
- Change oriented (effects of change)

2004

# Two types of LCA

- State-oriented (accounting)
- Change oriented (effects of change)



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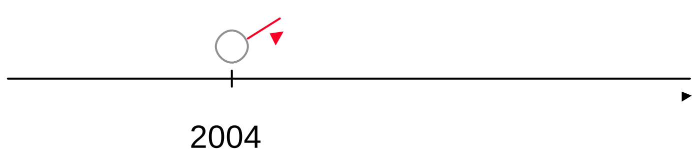
# Two types of LCA

- State-oriented (accounting)
- Change oriented (effects of change)

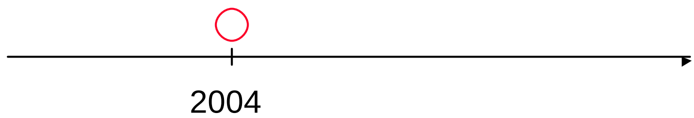



LCA and recycling of solar modules, Brussels, March 18-19 2004

# State-oriented LCA and GHG

- State-oriented (accounting)
- Change oriented (effects of change)

Is this a relevant state
for an analysis?







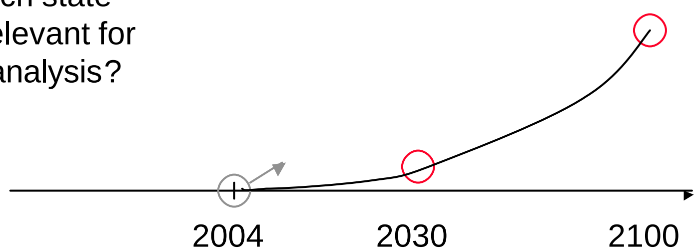

# GHG-emissions and PV

- Stock pollutants
- Small local emissions only contribute to <u>cumulative global emissions,</u> no direct local effects
- PV currently produce 0.01% of world electricity and 0.001% of world energy

# PV and GHG emissions

- State-oriented (accounting)
- Change oriented (effects of change)

Which state
is relevant for
an analysis?







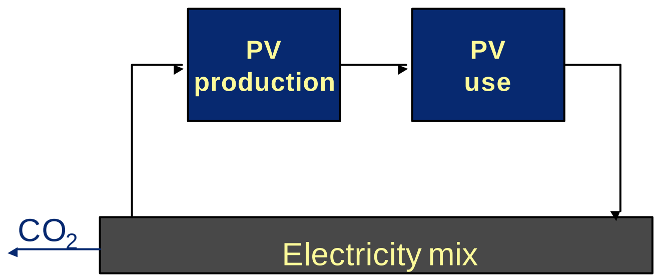

# State-oriented LCA

## PV and GHG emissions

- Future states with large PV penetration is more relevant than the current or historic situation!
- Changing the time horizon and scale of adoption effect methodological choices
  - Technical development (choice of data)
  - New combinations (functional unit)
  - Limited resources and byproduct markets (allocation)
  - Change of background systems (choice of data or system boundaries)

# Background systems

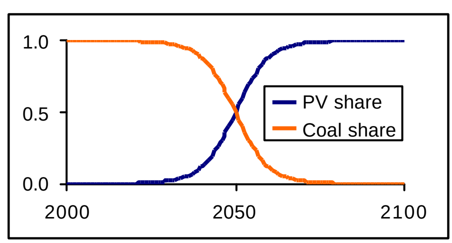
- Electricity mix will change over time
- Large scale PV adoption will change the electricity mix



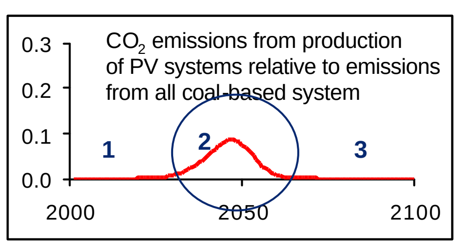




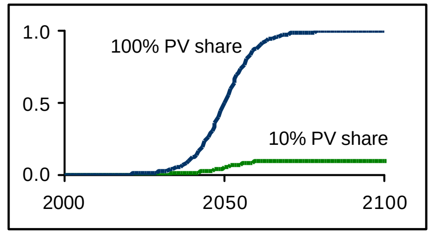

- Scenario approach




$CO_2$ emissions important in transition phase

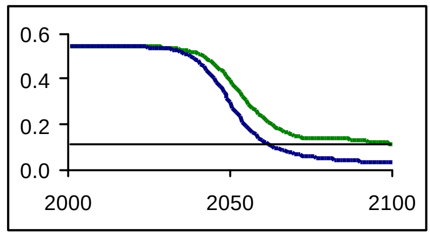


- Scenario approach




$CO_2$ emissions per kWh depend on potential to change the system

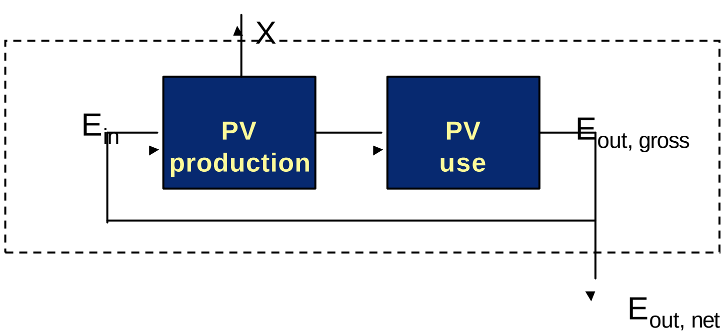
Cum prod. $CO_2$ emissions/cumulative el. gen








# 2. Net energy approach




$$E_{out, net} = E_{out, gross} - E_{in}$$

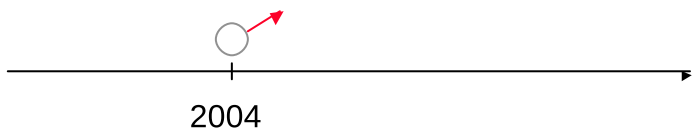
Non-electricity PV-specific environmental impact X is scaled up (not hidden in general energy system impacts)

# Change-oriented LCA
## PV and GHG emissions

-If I invest in that PV plant,
what is resulting environmental impact?

Change on the margin
Marginal data

Change-oriented
LCAs are
not additive








# Change-oriented LCA
## PV and GHG emissions

- Short term reversibel price effects
  - Inelastic (fixed) supply of resources
  - Elastic (flexible) demand of product


- Cumulative effects
  - Economies of scale and learning lead to decreased cost and increased adoption
  - Increased number of advocates and networks lead to change in institutions and attitudes

# Can the cumulative scale & learning effect be quantified?

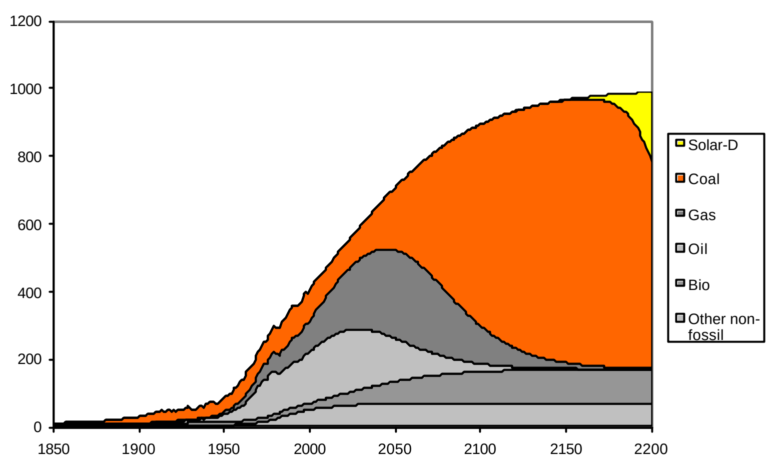
Contribution to avoided future emissions

- Estimate of the avoided emissions for large-scale adoption of PV
  - Baseline scenario
  - PV potential
  - Speed of diffusion
- Estimate of the contribution from one investment
  - Rate of cost reduction: Experience curve
  - Scope of learning
  - Target cost
  - Position on the experience curve

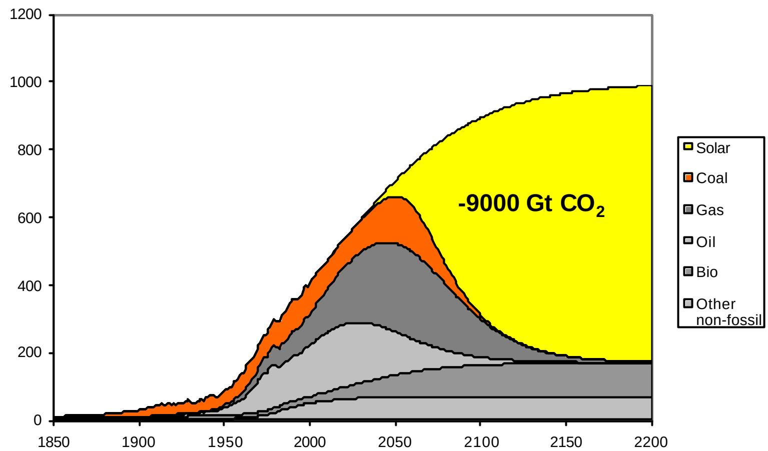




# Avoided emissions: Coal substitution



# Avoided emissions: Coal substitution



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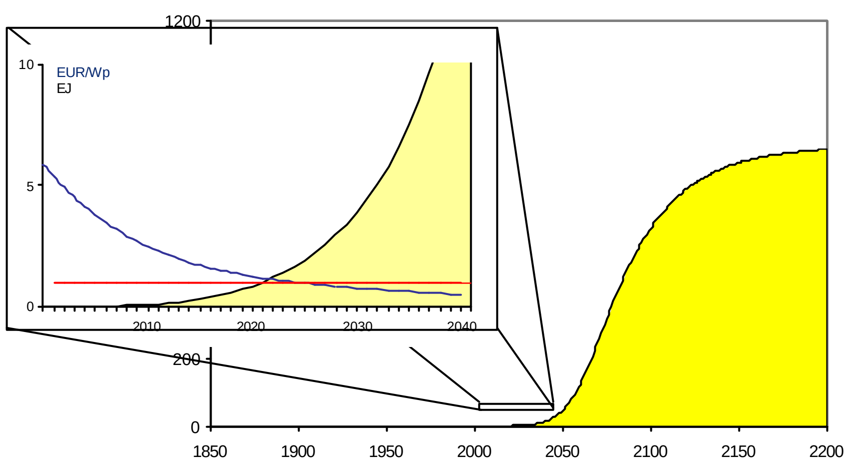
# Growth and cost reduction
## The experience curve




LCA and recycling of solar modules, Brussels, March 18-19 2004

# Emission effects on the margin:

## Technology, plant and production

Production (all energy from coal): **2-4 $kgCO_2/Wp$**

Avoided emissions PV-plant 2004: **-20- -40 $kgCO_2/Wp$**

Total cost of making PV competitive with coal: 180 GEUR
Total avoided emissions: 9000 Gt $CO_2$
=> 50 ton/EUR
Extra cost yr 2004 (5-1)= 4 EUR/Wp

⇒Technology learning effect on the margin 2004:
**-200,000 $kgCO_2/Wp$**





# Main message

Learning and potential to solve the problem needs to be made visible (i.e. quantified).

If this effect is not taken into account there is a risk that society invests to little in advanced technologies with short-term drawbacks but huge long-term advantages.

# Lessons for materials recycling

Materials handling crucial for potential (in particular for rare metals). Decreased energy paybacktime (important in transition).

Learning effects in recycling systems more important than enviromental efficiency over next 20 years

LCA methodology: Not hide PV specific issues in general energy enviromental effects -> specific materials cycles more important



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Questions?

LCA and recycling of solar modules, Brussels, March 18-19 2004

Science, Technology & Society

Natuurwetenschap & Samenleving

# Critical Issues in the Life Cycle Assessment of Photovoltaic Systems

Erik Alsema,

*Utrecht University, The Netherlands*

**Workshop on Life Cycle Analysis and Recycling of Solar Modules**

***18-19 March 2004, Brussels***

Universiteit Utrecht
Copernicus Institute
Department of Science, Technology and Society

## *Outline*

- *Critical issues in cell and module technology*
- *Energy Pay-Back Time & $CO_2$ emission*
- *Advanced cryst. silicon technology*
- *Future work*
- *Conclusions*



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Department of Science, Technology and Society

# I. Critical issues in cell technology



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# Issues for crystalline silicon

Key issues

- energy input for silicon purification and crystallization
- silicon losses
- silver consumption
- module recycling

Workshop on LCA and Recycling of Solar Modules,
Brussels, 18-19 March 2004

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## Issues for crystalline silicon (2)

Smaller issues:

- lead in solder and frit
- CFC/SF6 use
- sawing slurry waste
- risks from etchants



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## Issues for amorphous silicon

Key issues:

- silane safety risk
- energy consumption in production

Smaller issues:

- toxic gases
- higher BOS material requirements
- CFC or SF6 emission (reactor cleaning)



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# Issues for CdTe / CIGS

Main issues:

- toxic releases to environment (fires, waste handling)
- energy consumption in production
- reclaiming (toxic) materials from module waste
- resource availability (In, Ga)

Smaller issues:

- occupational health risks
- waste from reactor cleaning



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# Issues for BOS

- material for frames and support structure (aluminium?)
- inverter life time
- copper use

Workshop on LCA and Recycling of Solar Modules,
Brussels, 18-19 March 2004

Universiteit Utrecht
Copernicus Institute
Department of Science, Technology and Society

# II. Energy Pay-Back Time and $CO_2$ emissions

**General remarks:**

- Energy input is a major contributor to environmental impacts of PV systems;
- Energy input strongly determines greenhouse gas emission;
- Dependent on *irradiation* at installation location;
- $CO_2$ emission depends on *electricity supply* system;



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# Energy input present c-Si technology

| | mc-Si | sc-Si | unit |
|---|---|---|---|
| **process** | | | |
| **mg silicon production** | **450** | **450** | **MJ/m² module** |
| **silicon purification** | **1800** | **1800** | **MJ/m² module** |
| **crystallization & contouring** | **750** | **2300** | **MJ/m² module** |
| **wafering** | **250** | **250** | **MJ/m² module** |
| **cell processing** | **600** | **550** | **MJ/m² module** |
| **module assembly** | **350** | **350** | **MJ/m² module** |
| **Total module (frameless)** | **4200** | **5700** | **MJ/m² module** |
| ***Total module (frameless)*** | ***32*** | ***41*** | ***MJ/Wp*** |

***Source: Alsema,Energy Policy, 2000***

Workshop on LCA and Recycling of Solar Modules,
Brussels, 18-19 March 2004

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# Energy input a-Si module

Table 2
Breakdown of the energy requirement of an amorphous silicon thin-film module using present-day production technology (glass–glass encapsulation; in MJ of primary energy)

| Process | Energy requirements ($MJ_{prim}/m^2$ module) |
|---|---|
| Cell material | 50 |
| Module encapsulation material | 350 |
| Cell/module processing | 400 |
| Overhead oper. & equipment manuf. | 400 |
| Total module (frameless) | 1200 |
| Module frame (aluminium) | 400 |
| Total module (framed) | 1600 |

***Source: Alsema,Energy Policy, 2000***



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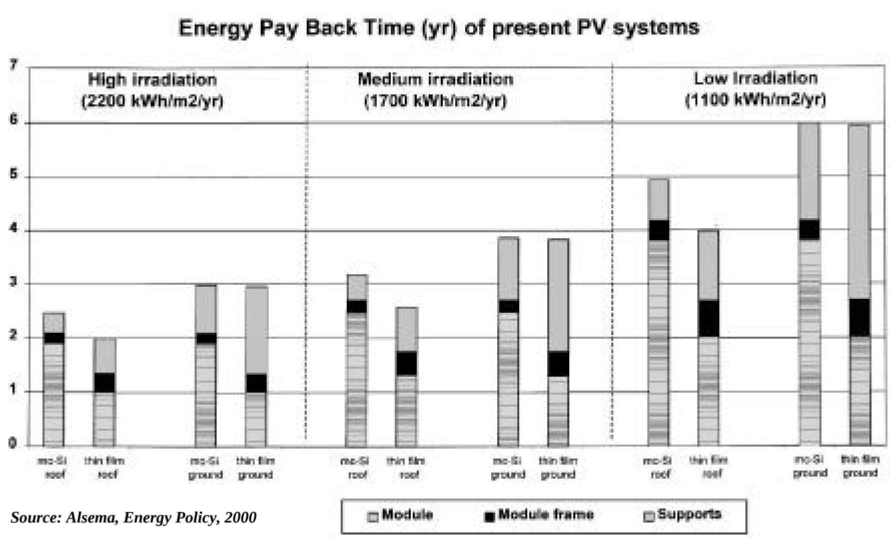


***Source: Alsema, Energy Policy, 2000***



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# III. LCA study on advanced c-Si technologies

**Study Objectives:**

- Comparison of three module production technologies:
  - "standard 2000" technology
  - SolSilc solar-grade Si + Ribbon-Growth-on Substrate (RGS)
  - Bayer/DS solar grade Si + EFG wafer
- Also: New inverter and roof integration concepts ("PV Wirefree")



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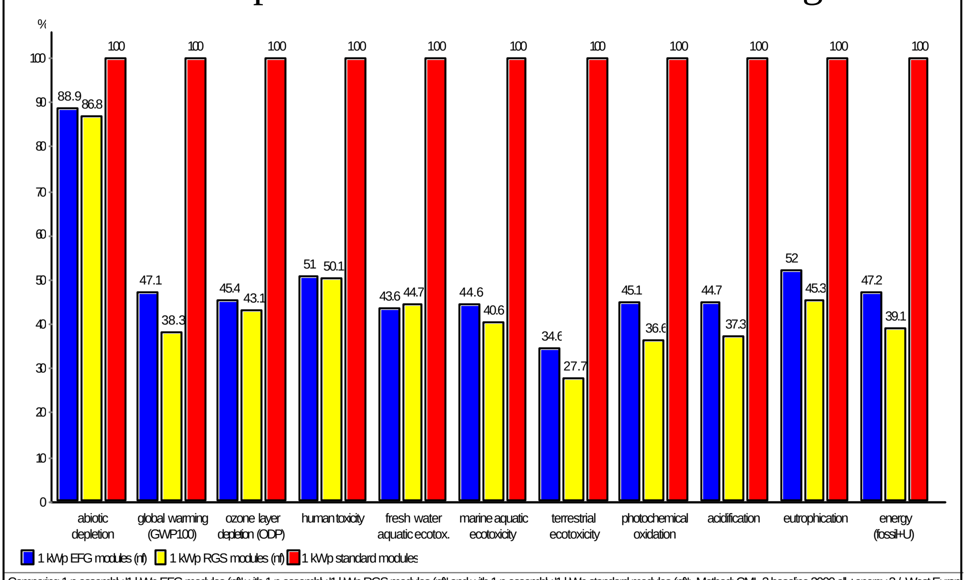
# LCA comparison of c-Si module technologies




**Source: Alsema, Sust. of adv. c-Si techn. , 2003**

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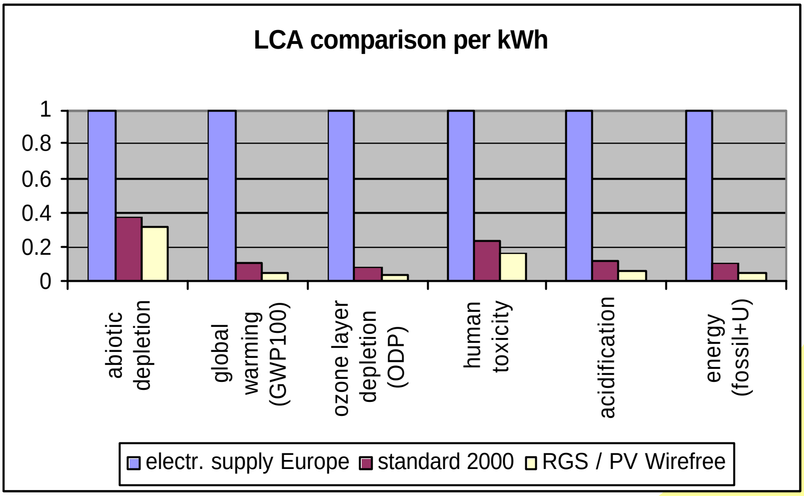
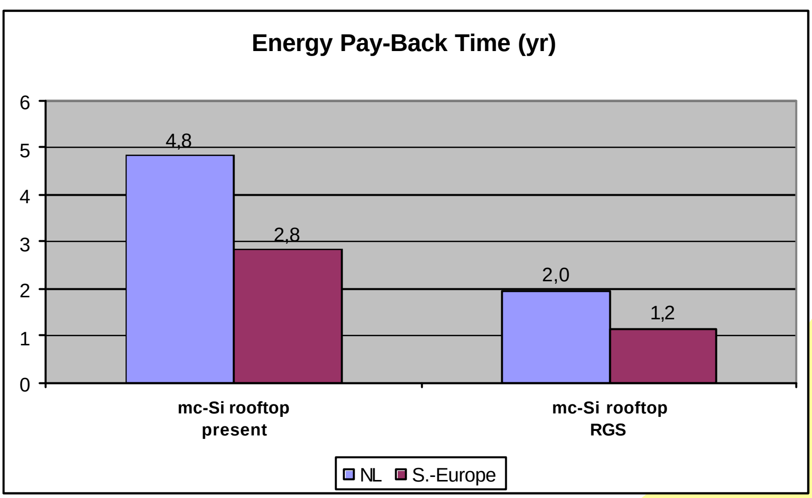


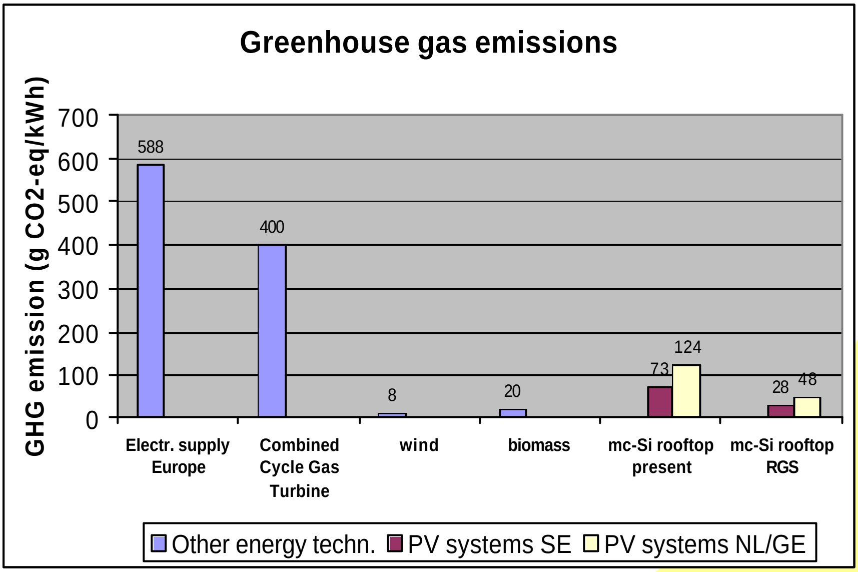

**Source: Alsema, Sust. of adv. c-Si techn. , 2003**



# EPBT Advanced Silicon




**Source: Alsema, Sust. of adv. c-Si techn. , 2003**




**Source: Alsema, Sust. of adv. c-Si techn. , 2003**



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# IV. Future Work

- Crystal Clear IP objectives:
  - achieve significant reduction in env. impact of c-Si modules;
  - develop and test module recyling technology;
  - establish *up-to-date* LCI data set for PV module production;
- Work on thin films ?
- Coordination between LCA activities (Crystal Clear, NEEDS, SENSE, Ecoinvent)



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# V. Final conclusions

- PV has very good potential as sustainable and significant energy source;
- Further improvement of the environmental profile is needed in the competion with other renewable options.



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# End

Workshop on LCA and Recycling of Solar Modules,
Brussels, 18-19 March 2004

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# Life Cycle Impact Analysis of Cadmium in CdTe PV Production

Vasilis M. Fthenakis

Environmental Sciences Department
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This assessment describes the material flows and emissions in all the life stages of CdTe photovoltaic modules, from extracting refining and purifying raw materials through the production, use, and disposal or recycling of the modules. The prime focus is on cadmium flows and cadmium emissions into the air. Previous studies are reviewed and their findings assessed in light of new experimental data obtained by high-energy synchrotron x-ray microprobe analysis at the National Synchrotron Light Source. Comparisons are also made of the cadmium environmental inventories in CdTe PV modules with those of Ni-Cd batteries and of coal fuel in power plants. The results of this study are projected into public policy decision-making options.

# Life Cycle Impact Analysis of Cd in CdTe PV Modules


Dr. Vasilis Fthenakis

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www.pv.bnl.gov

Professor of Earth & Environmental Engineering

Columbia University


Presentation at the EC Workshop on

Life Cycle Analysis & Recycling of Solar Modules, 18-19 March, 2004

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## NATIONAL PV EHS ASSISTANCE CENTER

- Investigate potential environmental, health and safety (EHS) hazards for new photovoltaic materials, processes and applications
- 180 Publications/Web Site (www.pv.bnl.gov)

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# CdTe PV Life-Cycle Stages (focus on Cd Flows –Air Emissions)

1. <u>Mining/Smelting/Refining</u>
2. Purification of Cd & Production of CdTe
3. Manufacture of CdTe PV modules
4. <u>Utilization of CdTe PV modules</u>
5. Disposal of spent CdTe PV modules

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# Perceptions

"**GreenPeace is deeply concerned** with the possibility of the CPA choosing to purchase solar modules that contain toxic metals…Current **CdTe panels** result in **Cd (gaseous) emissions of 0.5 g/GWh, equivalent to that of a coal fired power plant. The majority of these emissions (77%) result from <u>mining</u> and <u>utilization</u> of the modules** … "

*Comment to the California Power Authority, 2002*

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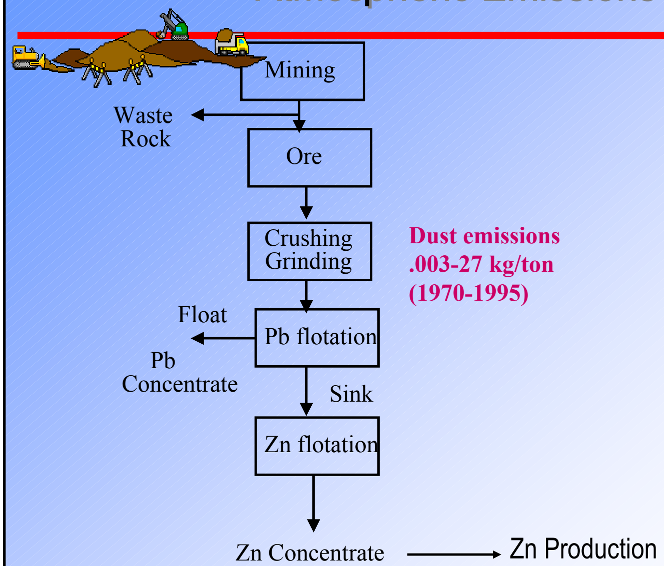
# Cd Flows in Zn Mining
# -Atmospheric Emissions-

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# Emissions Coefficients for Production of Toxic Heavy Metals

- Emission coefficients and estimates abound and differ
  (CGA 1973, 1981; Davis 1972; NAS 1980; PEDCo, 1980; NRC 1977, 1981; Nriagu 1980a, 1980b, 1980c; Niagu and Davidson, 1982; USEPA 1984; USEPA, AP-42, 1995; Liewellyn, US Bureau of Mines, 1994; Berdowski et al., Insp. Env., Netherlands;1995 ; Pacyna, EC, 1990)
- Best Approach -Combination of material balance and plant-specific emissions data
- Sources used:
  - US: Survey of (Cd Emission Sources (GCA, 1981; US Bureau of Mines, 1994; Plashy, USGS, 2001)
  - EC: Berdowski et al., 1995, 2003; Pacyna, 1990
  - UK: National Atmospheric Emissions Inventory, 2002
  - TeckCominco Trail plant, Canada, 1999-2003
  - Asarco Glove plant, Denver, 2000-2003

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# EC Emission Factors for Primary Zinc Production (g/ton product)

| | Germany 1991 | | Poland 1980-1992 | | Holland 1992 | Europe 2002 | |
|---|---|---|---|---|---|---|---|
| Compound | Thermal | Electrolytic | Thermal | Electrolytic | Electrolytic | Thermal | Electrolytic |
| **Cadmium** | 100 | **2** | 13 | **0.4-29** | **0.5** | 50[1] | **0.2** |
| Lead | 450 | 1 | 31-1000[2] | 2.3-467 | - | 1900 | - |
| Zinc | - | - | 420-3800 | 47-1320 | 120 | 16000 | 6 |

1 with Imperial smelting furnace.
2 limited abatement.

**Sources**: Berdowski et al., 1995, 2003; Pacyna, 1990

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# Production and Emissions at the Trail Smelter and Refineries, British Columbia, Canada [Teck Cominco Ltd, 2003]

| **Annual Production (ton)** | **1998** | **1999** | **2000** | **2001** | **2002** |
|---|---|---|---|---|---|
| | | | | | |
| Zinc | 274,300 | 288,700 | 272,900 | 168,100 | 269,000 |
| Lead | 63,900 | 75,700 | 91,300 | 55,200 | 80,700 |
| Cadmium | | 1,400 | 1,400 | 1,400 | 1,400 |
| Specialty Metals | | 28 | 28 | 28 | 28 |
| Silver | 463 | 431 | 463 | 348 | 670 |
| Gold | 3 | 2 | 2 | 2 | 5 |
| Fertilizer | 273,000 | 240,700 | 220,300 | 167,500 | 225,000 |
| **Cd Releases to Air from all Operations** (kg/yr) | | 600 | 250 | 100 | 95 |
| **(g of Cd/ton metal products)** | | **1.64** | **0.69** | **0.45** | **0.27** |
| **Cd Releases to Water from all Operations** | | | | | |
| (kg/yr) | | 208 | 290 | 170 | 208 |
| (g of Cd/ton metal products) | | 0.57 | 0.79 | 0.76 | 0.59 |
| | | | | | |

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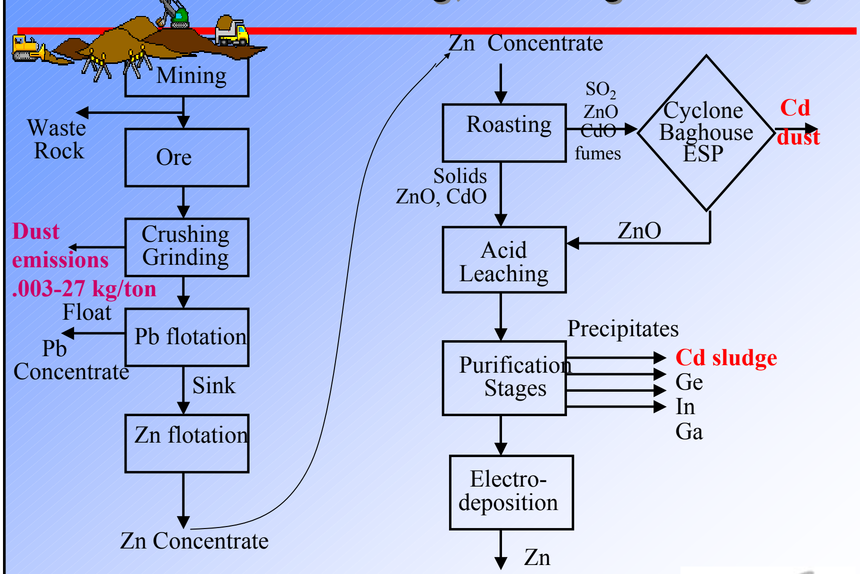
# Cd Flows in Zn Mining, Smelting & Refining

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# Cd Emissions from Mining/Smelting: Facts

1. Cd is a **byproduct of Zn**, Cu and Pb production. The main resource of Cd is CdS in sphalerite (ZnS) ores. The Zn/Cd ratio is 200/1 to 350/1.
2. **Production of Cd uses <u>emissions and waste</u> of Zn production**
3. **Cd output is dependent on Zn production, not on Cd demand**
4. Before Cd production started in the US, ~85% of Cd from Zn concentrates was lost to the environment
5. Zinc mines in the US also produce:
   100 % of **Cd, Ge, In,** Th
   10 % of **Ga**
   3 % of Au,
   4 % of Ag

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## Emissions Allocation based on Material Output from Zn-ore

| Metal | Typical Grade in ore (ppm) | Emissions Allocation (%) |
|---|---|---|
| Zn | 40000 | 99.44 |
| Cd | 200 | 0.50 |
| Ge | 20 | 0.05 |
| In | 4 | 0.01 |

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## Emissions Allocation based on the Economic Value of Products from Zn-ore

| Metal | Typical Grade ore (ppm) | Prices 1998* ($/kg) | Primary Production ($10^3$ ton/yr) | Production Economic Value ($10^6$ $/yr) | Emissions Allocation (%) |
|---|---|---|---|---|---|
| Zn | 40000 | 1.1 | 7000 | 7700 | 97.82 |
| Cd | 200 | 0.6 | 20 | 46 | 0.58 |
| Ge | 20 | 1700 | 0.05 | 70 | 0.89 |
| In | 4 | 306 | 0.2 | 56 | 0.71 |
| Total | | | | 7872 | 100 |

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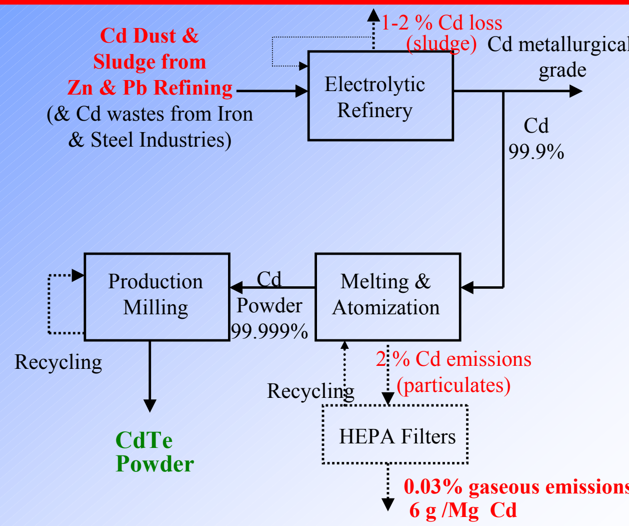
# Cd Flows from Cd Concentrates to CdTe

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# Cd Emissions in CdTe PV Manufacturing

- High-Rate Vapor Transport Deposition

35-70% material utilization
Residuals are recycled
1% of vapors carried in exhaust
99.97% collection via HEPA filters

Controlled Cd emissions=3 g/Mg
Cd input

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# Utilization of CdTe PV Modules

- **Zero emissions under normal conditions**
  (testing in thermal cycles of –80 C to +80 C)
- **No leaching during rain from broken or degraded modules** (Steinberger, 1997)
- **Debate on fire risks**
  - Thermogravimetric tests on CdTe powder and single-glass CdTe PV (Steinberger, 1998)
  - Glass-CdTe-Glass PV

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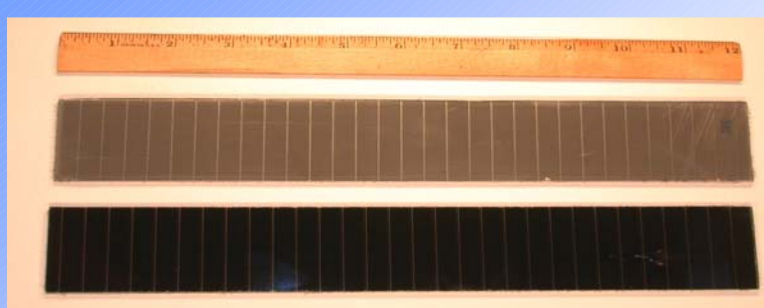
# CdTe PV sample for fire-simulation experiments



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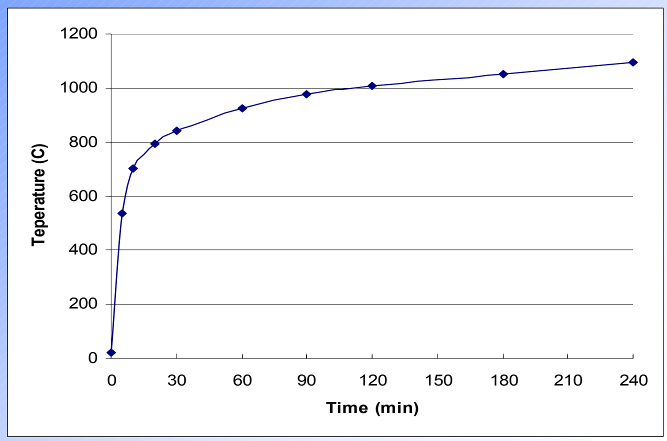
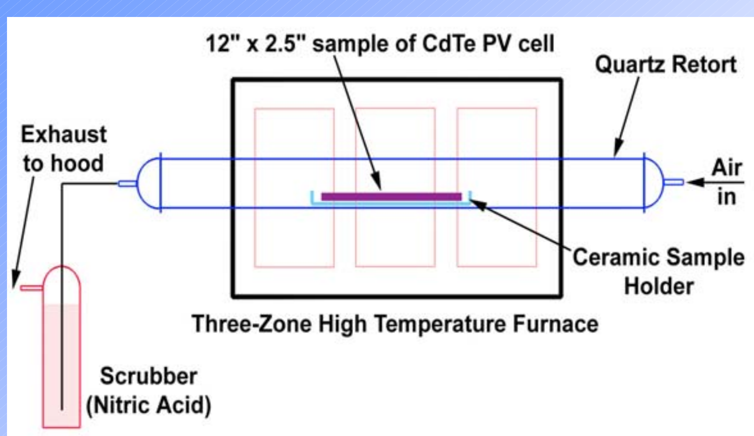
# Fire Simulation -Test Protocols

- UL 1256 30 min @760 C
- ASTM E119-98 Standard Temperature Curve






# Fire Simulations Experimental Set-up

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## Fire-simulation Experiments

- Weight Loss Measurements
- ICP Analysis of Cd & Te Emissions
- X-ray Fluorescence Micro-Spectrometry of Cd in Heated Glass
- ICP Analysis of Cd & Te in Heated Glass



## Thermogravimetric & Emissions Analysis

| **Temp (C)** | Weight Loss (% sample) | **Cd Loss (% Cd)** | Te Loss (% Te) |
|---|---|---|---|
| **760** | 1.9 | **0.6** | 0.4 |
| **900** | 2.1 | **0.4** | 1.2 |
| **1000** | 1.9 | **0.5** | 11.6 |
| **1100** | 2.2 | **0.4** | 22.5 |

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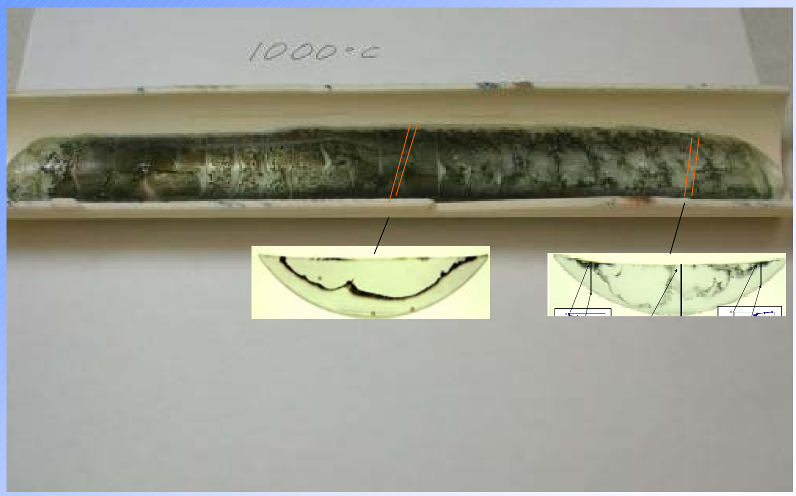
## Heated Sample –1000 C

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## Heated Sample –1100 C

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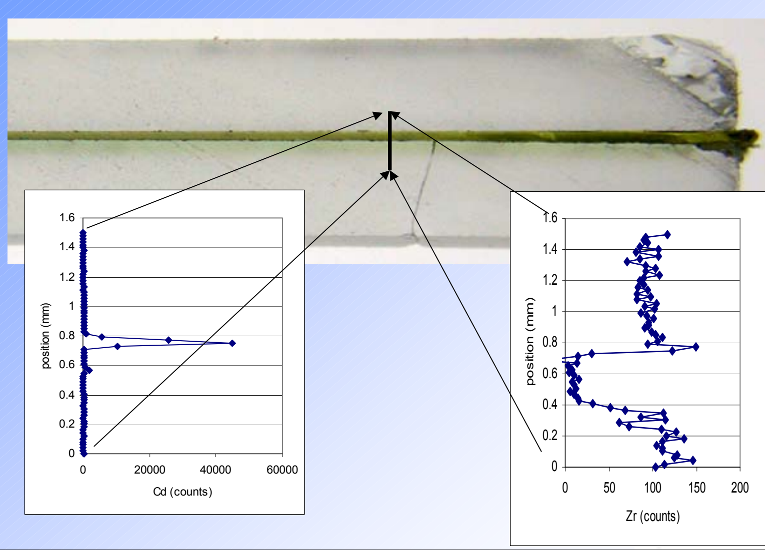
# National Synchrotron Light Source

Provides small, intense beams of X-rays for many analytical techniques:

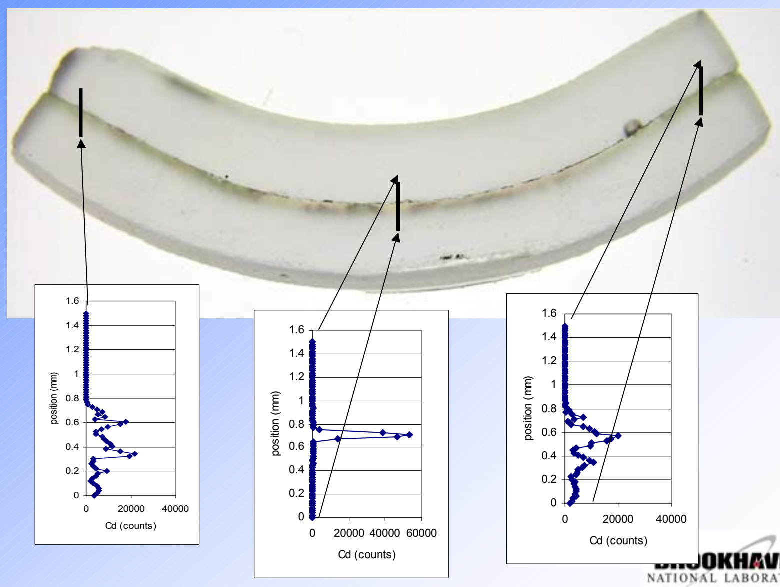
**Microbeam x-ray fluorescence (XRF)**
ppm to ppb sensitivity for many elements

**X-ray absorption spectroscopy (XAS)**
metal redox state, atomic coordination

# XRF-micro-probing -Cd & Zr Distribution in PV Glass Unheated Sample -Vertical Cross Section



## XRF-micro-probe -Cd Distribution in PV Glass
## 760 °C, Section taken from middle of sample

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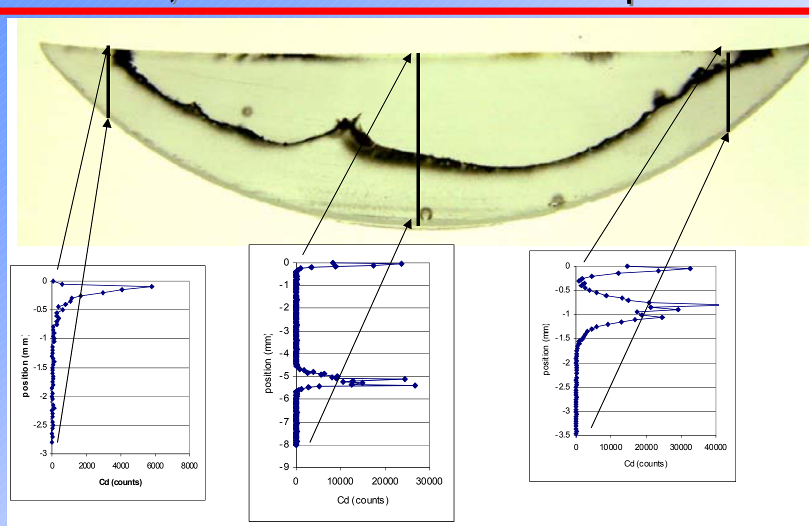
## XRF-micro-probe -Cd Distribution in PV Glass
## 1000 °C, Section taken from middle of sample

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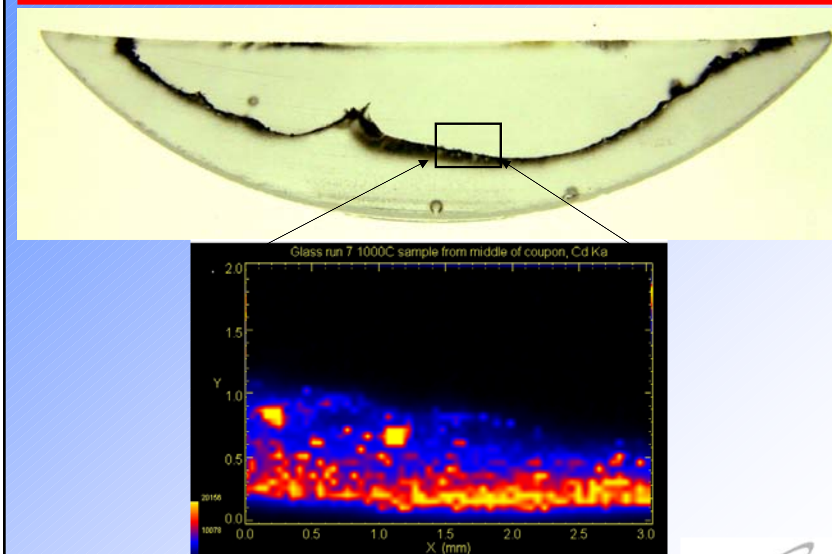
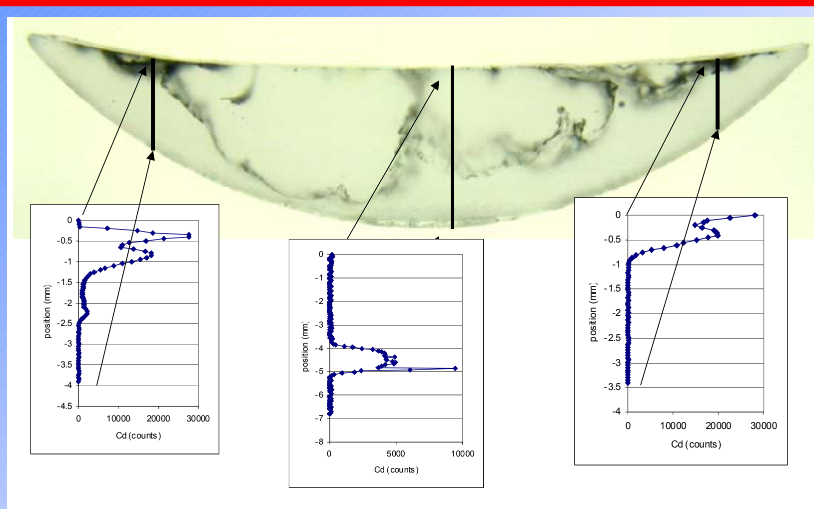
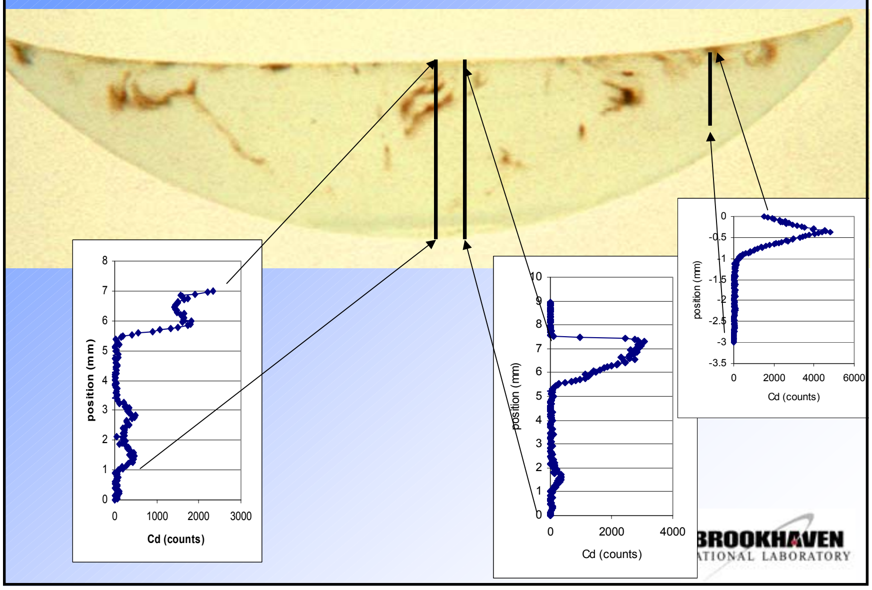
# XRF-micro-spectroscopy -Cd Mapping in PV Glass 1000 °C, Section taken from middle of sample




# XRF-micro-probing -Cd Distribution in PV Glass 1000 °C, Section taken from right side of sample



## XRF-micro-probing -Cd Distribution in PV Glass 1100 °C, Section taken from middle of sample

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## Decommisioning of end-of-life CdTe PV modules

- Concerns about leaching from PV disposed in municipal landfills
- This issue is not unique to CdTe PV
  - TCLP –US-EPA
  - DEV -Germany
  - STLC and TTLC –California HWCL
- Concerns about PV modules in MW incinerators,
- Recycling will resolve these concerns
- Recycling is technically feasible and cost is not excessive

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## Atmospheric Cd emissions from the Life-Cycle of CdTe PV Modules –Reference Case

| Process | Air Emissions (g Cd/ton Cd*) | Allocation (% ) | Air Emissions (mg Cd/GWh) |
|---|---|---|---|
| 1. Mining of Zn ores | 2.7 | 0.58 | 0.02 |
| 2. Zn Smelting/Refining | 40 | 0.58 | 0.30 |
| 3. Cd purification | 6 | 100 | 7.79 |
| 4. CdTe Production | 6 | 100 | 7.79 |
| 5. CdTe PV Manufacturing | 3 | 100 | 3.90 |
| TOTAL EMISSIONS | | | 19.80 |
| *ton of Cd used in manufacturing | | | |

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## Atmospheric Cd emissions from the Life-Cycle of CdTe PV Modules –Worst Case

| Process | Air Emissions (g Cd/ton Cd*) | Allocation (%) | Air Emissions (mg Cd/GWh) |
|---|---|---|---|
| 1. Mining of Zn ores | 27 | 0.58 | 0.29 |
| 2. Zn Smelting/Refining | 1000 | 0.58 | 10.76 |
| 3. Cd purification | 12 | 100 | 22.26 |
| 4. CdTe Production | 12 | 100 | 22.26 |
| 5. CdTe PV Manufacturing | 6 | 100 | 11.13 |
| TOTAL EMISSIONS | | | 66.71 |
| *ton of Cd used in manufacturing | | | |

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# Cd Use in CdTe PV Production

Cd is produced as a byproduct of Zn production
and can either be put to **beneficial uses** or **discharged** into the environment

- Above statement is supported by:
  - US Bureau of Mines reports
  - Rhine Basin study (the largest application of Systems Analysis on Industrial Metabolism)

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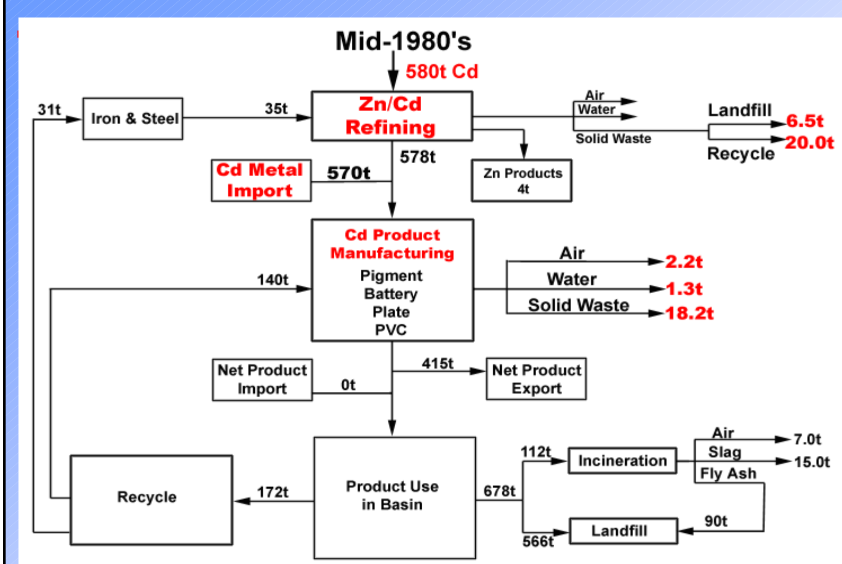
# Cd Flow in the Rhine Basin




*Source:* *Stigliani & Anderberg, Chapter 7, Industrial Metabolism, The UN University, 1994*

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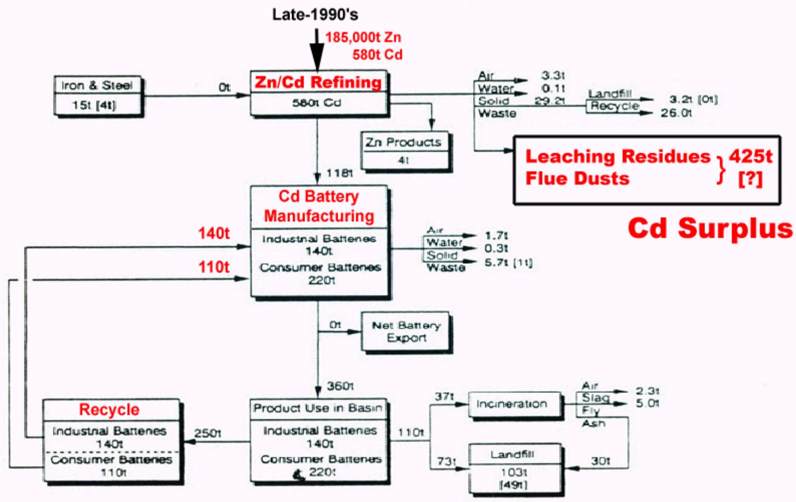
# Rhine Basin: Cd Banning Scenario




*Source:* *Stigliani & Anderberg, Chapter 7, Industrial Metabolism, The UN University, 1994*

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# Cd Use & Disposal in the Rhine Basin: The effect of banning Cd products

*"So, the ultimate effect of banning Cd products and recycling 50% of disposed consumer batteries may be to shift the pollution load from the product disposal phase to the Zn/Cd production phase. This does not imply that banning Cd-containing products is not a wise strategy; rather, it indicates that **if such a ban were to be implemented, special provisions would have to be made for the safe handling of surplus Cd wastes generated at the Zn refineries!***

*One possible option would be to allow the production and use of Cd-containing products with inherently low availability for leaching. The other option, depositing the Cd-containing wastes in safely contained landfills, has other risks"*

*Source:* *Stigliani & Anderberg, Chapter 7, Industrial Metabolism, The United Nations University, 1994*

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# Cd vs. CdTe PV

| Compound | $T_{melting}$ (°C) | $T_{boiling}$ (°C) | Solubility (g/100 cc) | Toxic/ Carcinogen |
|---|---|---|---|---|
| Cd | 321 | 765 | insoluble | yes |
| $Cd(OH)_2$ | 300 | - | 2.6e-04 | yes |
| CdTe | 1041 | - | insoluble | ? |

• CdTe is much more stable than Cd and $Cd(OH)_2$ used in batteries

• In addition, CdTe in PV is encapsulated between glass sheets

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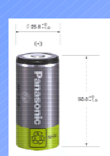
# NiCd Battery to CdTe PV Comparisons




10 g Cd / C-size

7 g $Cd/m^2$

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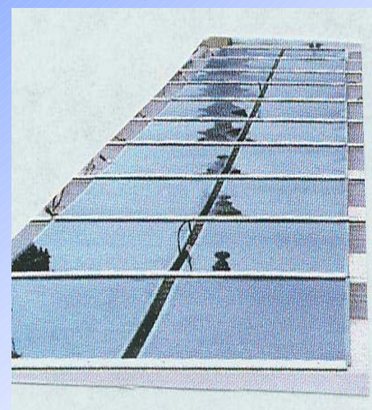
# NiCd Battery to CdTe PV Comparisons

**7 batteries = 70 g Cd = 1 kW CdTe PV**

**3265 kg Cd/GWh**



**1.3 kg Cd/GWh**

**•Cd in CdTe PV generates 2,500 times more electricity than NiCd batteries**

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# Cd from Coal-burning Power Plants

- Cd Air Emissions
  - 2 g/GWh (median); 7.2 g/GWh (average) *(EPRI database)*
    - Assuming Cd Removal of 98.6% in ESPs
    - Cd in coal: 0.5 ppm (median); 1.8 ppm (average)
- Cd Fine Dust
  - 140 g/GWh
- Other Emissions
  - $CO_2$: 1000 ton/GWh
  - $SO_2$: 8 ton/GWh
  - NOx: 3 ton/GWh
  - $PM_{10}$: 0.4 ton/GWh
  - Mercury, Arsenic, Dioxins, etc

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# Conclusions

- Cd is produced as a byproduct of Zn production and can either be put to *beneficial* uses or *discharged* into the environment
- CdTe in PV is much safer than other current Cd uses
- CdTe PV uses Cd 2500 times more efficiently than NiCd batteries
- Air emissions of Cd from the Life Cycle of CdTe PV are 100-360 times lower than Cd emitted into air from coal power plants that PV replaces

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# 20 Years of Module Testing – Lessons Learned

T. Sample

European Commission, DG Joint Research Centre
Institute for Environment and Sustainability, Renewable Energies Unit,
Ispra, Italy

## *ABSTRACT*

Since 1981 the European Solar Test Installation (ESTI) of the European Commission's Joint Research Centre has been performing qualification tests on terrestrial photovoltaic (PV) modules. Since 1990, the test standard applied is IEC 61215, or it's direct predecessor, Specification 503. The presentation describes the results of more than 148 module types tested, focusing on the reliability and lifetime. The results from field exposure of 20 years are also discussed from the 10kWp plant at TISO and from the outdoor field at ESTI.

## *INTRODUCTION*

Since 1981, Terrestrial Photovoltaic (PV) Modules have been rigidly tested at the European Solar Test Installation (ESTI) of the European Commission's Joint Research Centre, to a progressive set of standards which evolved along increasing experience with applications and manufacturing methods. Originally, the test standards developed at ESTI served to accompany the first pilot- and demonstration programmes funded by the European Commission, and was to ensure that such publicly funded systems were made from highest-quality PV products.

## *THE IEC STANDARD 61215*

The International Electrotechnical Commission (IEC) developed the IEC 61215 standard, within it's Technical Committee 82, Solar Photovoltaic Energy Systems, which was published in 1993 [1]. This standard is based on previous test-specifications in use in the US, Japan and Europe. The standard "*lays down IEC requirements for the design qualification and type approval of terrestrial photovoltaic modules suitable for long-term operation in general open-air climates, …*". The standard contains test levels and a test sequence, and specifies it's purpose as "*…to determine the electrical and thermal characteristics of the module and to show, as far as is possible within reasonable constraints of cost and time, that the module is capable of withstanding prolonged exposure in climates described in the scope. The actual lifetime expectancy of modules so qualified will depend on their design, their environment and the conditions under which they are operated. …*"

## *ACCELERATED TESTS TO IEC 61215 AND CEC 503*

A summary of the modules tested between 1990 and the end of 2003 is given in table 1. The points to be noted from this table are that around 12% of the modules tested do not pass the IEC 61215, and that this overall failure rate has remained relatively constant with time.

**Table 1.** Summary of modules tested from 1990 until end 2003.

| | 1990-1995 | 1996-2003 | Total |
|---|---|---|---|
| Modules Tested | 67 | 81 | **148** |
| Full Programme | 37% | 23% | **30%** |
| Extension | 63% | 77% | **70%** |
| | | | |
| Passed | 60% | 69% | **65%** |
| Passed after Re-Test | 30% | 17% | **23%** |
| Failed | 10% | 14% | **12%** |

However, it is worthwhile to note, that in the period 1996 to end 2003, the number of full test programmes decreased in favour of more qualification extension tests. Manufacturers were more often modifying already approved products rather than developing entirely new modules. The risk involved can be drawn from the fact that only 9 of the 19 new module types undergoing full qualification tests passed the sequence immediately; 5 needed to repeat tests to achieve type approval and 5 were rejected, which corresponds to a reject rate of 26%, much above the average. This probably reflects the increasing number of new module manufacturers in the past 5 years, which either need to gain experience in manufacturing quality control, or embark with new technical design features.

The IEC Module Type Approval tests have been proven to address design problems of commercial modules very well. Also, feedback from operational PV-installations confirms acceleration factors, and defects detected already during the qualification tests.

## *OUTDOOR EXPOSURE*

Results obtained on the study of the oldest grid connected PV plant in Europe show that, although it is not looking good from a visual aspect, the system is working in a very satisfactory manner [2].

The Arco Solar ASI 16-2300 modules proved to be remarkably resistant, showing that 20-year old technology was very good.

Regarding the determination of the Mean Time Before Failure of the plant, it is reasonable to assume, on the basis of results obtained from accelerated lifetime tests, that the modules could continue to provide useful electrical power for another 10-15 years. This estimate significantly changes the economy of the system, as it greatly extends the mean lifetime of the plant.

Initial indications from a range of modules exposed for 20 years at the ESTI outdoor test site [3] tend to re-enforce the findings of the TISO plant. Of the 40 modules from 5 manufacturers currently analyzed over 93% have retained more than 80% of the original measured power. In many cases the modules are in a poor optical condition with extensive yellowing and some delamination, but they still produce a significant % of their original power.

## *CONCLUSIONS*

Type approval testing, through various specifications up to the current IEC 61215 type approval standard, has contributed to the high standard of PV modules produced during the last 20 years. A combination of the results from accelerated testing and the results obtained from field exposure give a high confidence for the 20-year warrantees commonly stated by manufacturers. Indeed module and system lifetimes in excess of 20-years can be expected on the basis of useful power production.

Non-uniform visual aging of modules may represent a greater problem in building integrated systems if the building owners dislike the visual impact.

## *REFERENCES*


[1] IEC 61215: 1993; IEC Central Office: Crystalline Silicon Terrestrial Photovoltaic Modules – Design qualification and Type approval.

[2] A. Realini, E. Burà, N. Cereghetti, D. Chianese, S. Rezzonico, T. Sample and H. Ossenbrink; STUDY OF A 20-YEAR OLD PV PLANT (MTBF PROJECT), Proceedings 17$^{th}$ European Photovoltaic Solar Energy Conference, Munich (2001) p 447-450

[3] D. Halton and E. Dunlop, Private communication, ESTI (2004)

# 20 YEARS OF MODULE TESTING - LESSONS LEARNED

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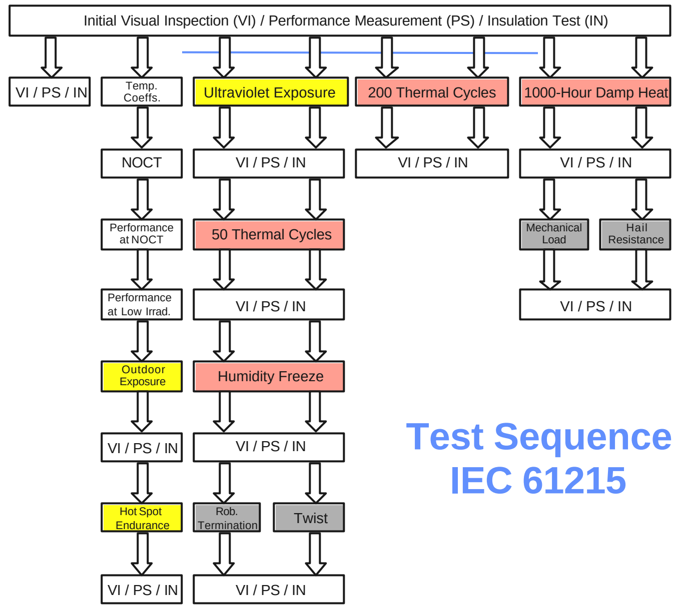
Ispra, Italy

**Workshop on Life Cycle Analysis and Recycling of Solar Modules , March 18-19, 2004 Brussels, Belgium**



## Introduction

- **Operating lifetime is one of the four factors determining cost of PV electricity**
- **Important to determine lifetime for**
  - Build-up of User Confidence
  - Warranty issues
- **Reliability testing has been performed since 1980 under a variety of Specifications and Standards**
  - ESTI: 1981 Spec 501; 1985 Spec 502; 1990 Spec 503; 1993 IEC 61215



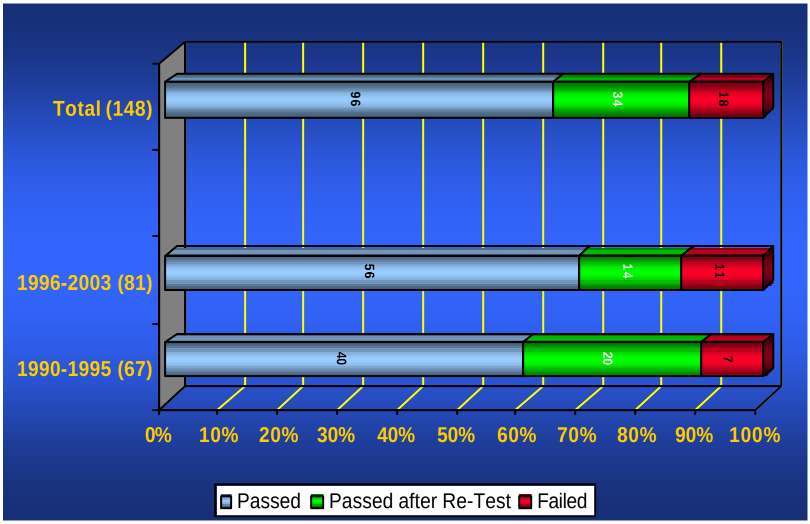

## Test Sequence IEC 61215



## IEC Standard 61215 Pass/Fail Criteria

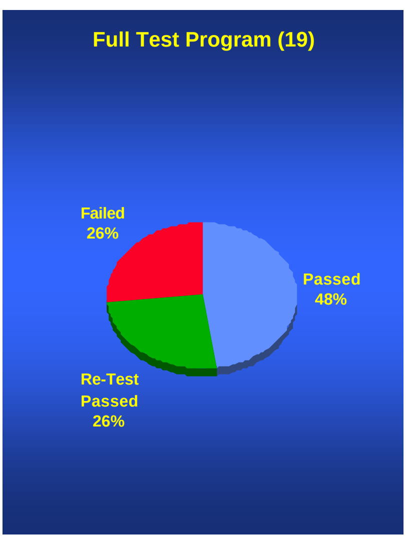
- **Published in 1993**
- **"Requirements for Design Qualification and Type Approval"**
- **Between the tests:**
  - Visual Inspection, Performance and Insulation tests
- **Modules fail with**
  - Visible defects
  - Circuit Faults (Open Circuit or Grounding)
  - Performance Loss > 5%/8%
  - Insulation Failures

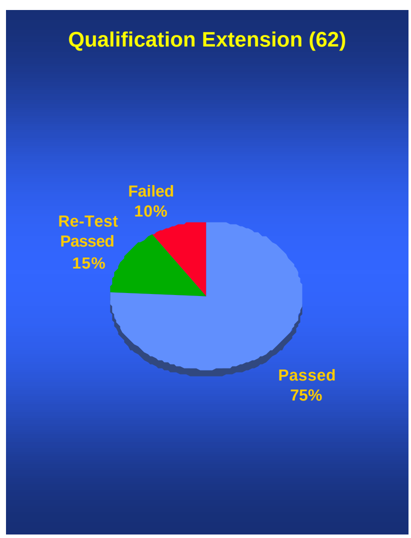
## Pass/Fail Summary 1990..2003



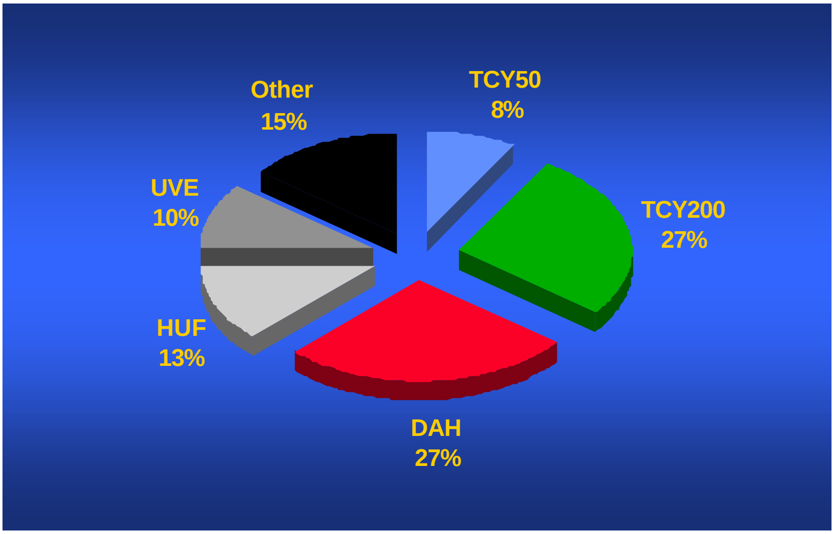



## Pass rate: Full Tests vs. Extension 1996-2003



## Tests Provoking Failures





○ Renewable Energies
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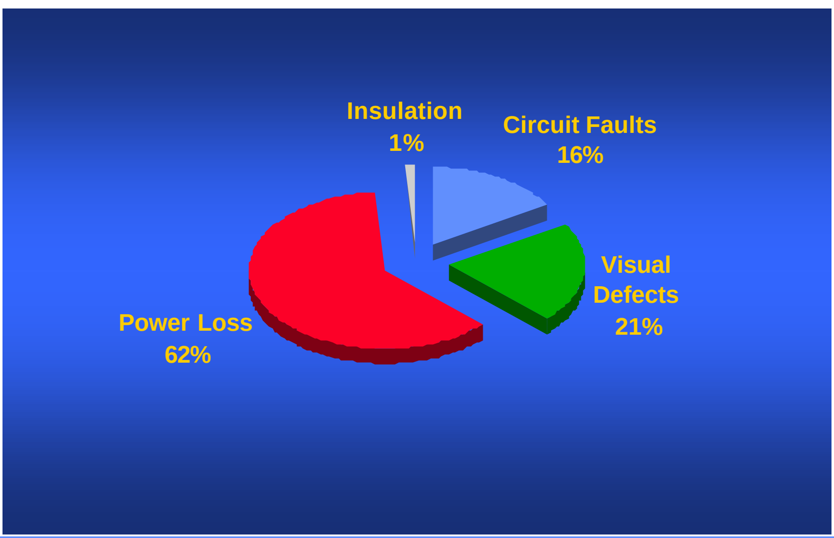
EUROPEAN COMMISSION

## Types of Major Defects





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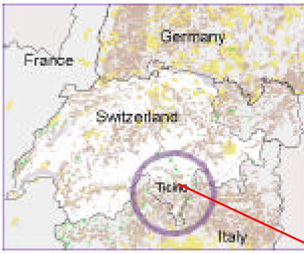
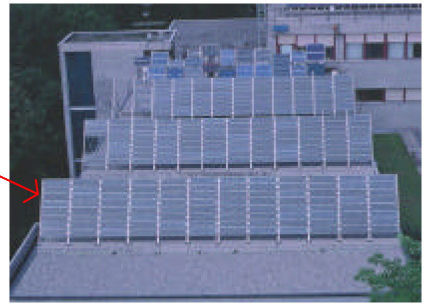
## Field Observations 20 Year-Old TISO Plant




### 10 kW PV plant



252
(12 strings of 21 panels each)

Arco Solar

ASI 16-2300 modules

35 cs-Si cells, PVB encapsulant, Tedlar/Al/Tedlar backsheet

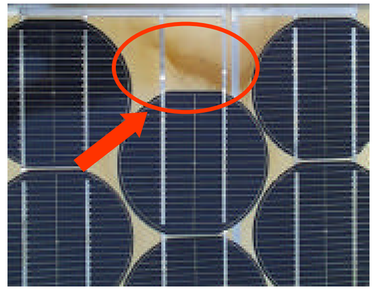


## Indoor IV Measurements: Reference Modules

- **18 modules reference modules**
  - ESTI laboratory systematic IV measurements - since 1982
- **13 stable modules**
  - power loss: -1.7% vs 1982 mean $P_{max}$
- **5 degraded modules**
  - power loss: -9.1% vs 1982 mean $P_{max}$
  - (2 hot-spot, 1 damaged cell)

## Visual Defects: Yellowing

- **Yellowing**
  - 98% of modules
  - (~50% in 1985)
  - 78% exhibiting complete coverage of tedlar
  - (63% dark yellowing)

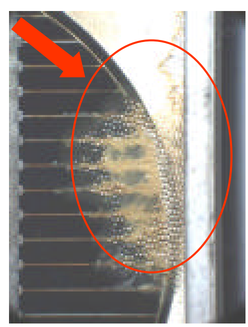


No influence on encapsulant transparency
(same spectral response for white and yellow modules)



## Visual Defects: Delamination

- **92% of modules**
  - (74% in 1996)
- **27% major defect**
  - IEC 61215



- No effects on module insulation
  (dry & wet insulation tests)
- Little effect on module performance
  (cells delamination, total delaminated area)

## Summary of the 10 kW plant

- **Not good looking, but perfectly functioning plant**
- **Remarkable module resistance**
- **Good 20 year-old technology**
- **Lifetime of around 30 years?**



## ESTI Outdoor Experience

- **Initial results from 40 modules (5 Manufacturers)**
- **Similar results to the TISO plant,**
  - 93% of the modules retain more than 80% of original power
- **In many cases poor visual condition**
  - Yellowing
  - some delamination

## Conclusions

- Design and manufacturing process control problems of PV modules well revealed
- Feedback from field-tests confirms accelerated testing
- >20 years lifetime ensured
- Most of failure mechanisms well understood
- Client acceptance may be dominated by visual impact, not performance



## Acknowledgements

**The Current ESTI Type Approval team:**

- Mike Field
- George Nicol
- Pier Biavaschi
- Massimo Della Rossa, the Quality Manager

**and past members to numerous to list but not forgotten**

# Performance of PV systems under real conditions

Thomas Nordmann, Ulrike Jahn and Wolfgang Nasse

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### *Purpose of the work*

The purpose of this work is presenting and comparing operational performance results of grid-connected PV systems, as collected and elaborated for the Photovoltaic Power Systems Programme of the International Energy Agency (IEA). The general objective of this Task is to provide PV experts, research laboratories, PV industry, utilities and other target audiences with detailed information on the operational performance results and reliability of PV systems and subsystems.

### *Approach*

Task 2 has collected information on the technical performance, reliability and cost of PV systems located in 15 countries. The information is entered into a Performance Database, which allows the user to select PV system data, monitoring data and calculated results as well as to export these data into spread sheet programmes. Task 2 participants have analyzed performance and reliability data for PV systems and components, both in order to ensure the quality and comparability of information in the Performance Database and to develop analytical reports on key issues. Activities to date include the work on the availability of irradiation data, tools for checking the performance of PV systems, shading effects and temperature effects as well as long-term performance and reliability analysis.

This paper focuses on the final results on long-term performance and reliability issues of selected PV systems in different countries in Europe and in Japan. Particularly complete data sets and results are available from 330 grid-connected PV systems ranging from small-decentralized systems (PV roofs), dispersed systems (BIPV, sound barrier) to centralized systems (PV power plants). Performance ratios (PR) obtained from PV installations in different countries are compared on monthly and annual basis. Building integrated as well as non-integrated PV systems are compared with respect to performance ratio and reliability. Energy efficiency values of various PV array and inverter set-ups are also pooled and presented. Reduced yield analysis is summarized and demonstrated in case studies of selected PV installations.

### *Scientific innovation and relevance*

The relevance of this work is manifold for further successful implementation of latest PV technology. The existing and updated Performance Database comprising a collection of high quality operational data aims at providing a unique tool for PV system performance analysis and comparison. This tool can be used to check the operational behaviour of existing PV plants and to illustrate the performance patterns expressed in standard quantities. Additionally, reliable and world-wide monitoring performance data and results underpin and support future developments for feed-in-tariffs and other financing schemes to stimulate the PV market.

### *Results*

Comparing early PV installations (1991-1994) and new installations (after 1996) in Germany, a significant rise in mean annual PR of 13% was found. The high level of average PR (0.74) and nearly constant annual PR values during five operational years (1998-2002) indicate that the quality of the late systems in Germany has clearly increased. Similar results were gained for the 334 investigated grid-connected PV systems in 11 countries. Detailed results on performance, efficiency and reliability issues will be presented for early installations as well as for state-of-the-art PV systems.

### *Conclusions*

The conclusions of this work allow to state trends on long-term performance analysis and reliability of grid-connected PV systems in different countries in Europe and in Japan. This includes recommendations on improved PV system design and installation gained from reduced yield analysis on well-monitored PV systems under special investigation.

## *Explanatory pages*

This paper presents operational performance results of grid-connected PV systems, as collected and elaborated for the Photovoltaic Power Systems Programme of the International Energy Agency (IEA). Performance indicators obtained from 372 PV installations in different countries are compared and discussed. Results of Task 2 international collaborative work include:

### *PV Performance Database*

The IEA Performance Database contains high quality data of 372 monitored PV plants with an installed capacity of more than 12 MWp adapted to various applications (power supply, domestic uses, rural electrification, professional applications). The data are made available to the user through internal graphical displays and reports and by exporting the data into a standard spread sheet programme. Figure 1 shows the distribution of monthly monitoring data in 15 countries for the years 1986 to 2002.

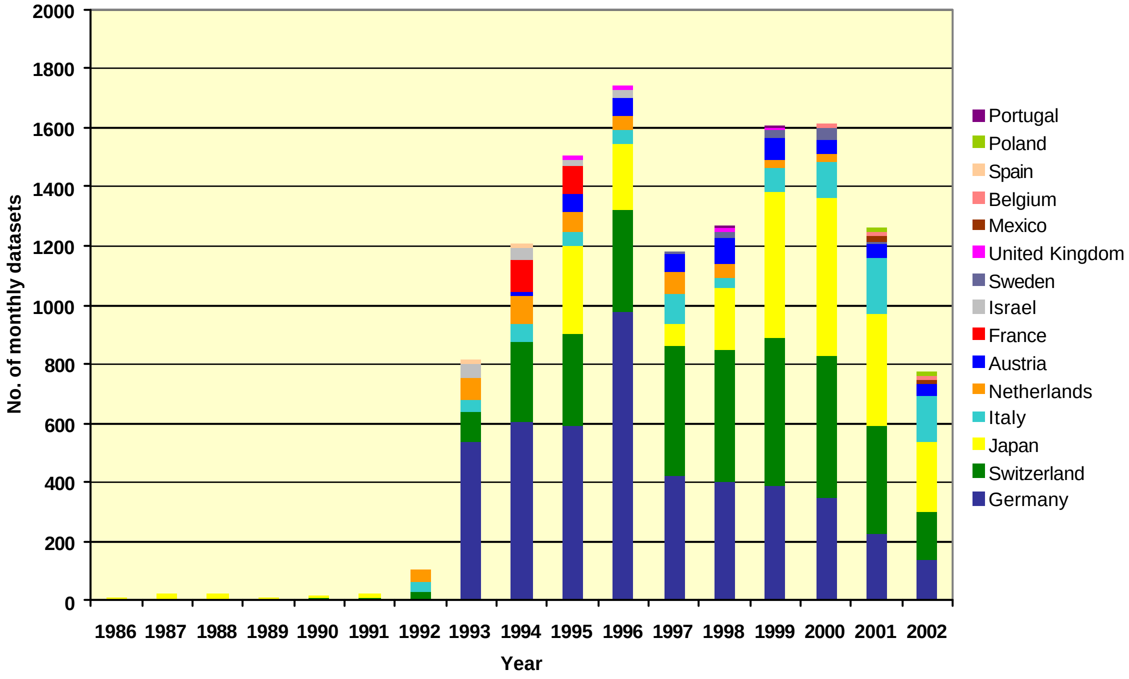


Figure 1: Overview of collected monitoring data in the Task 2 Performance Database

### *Trends on long-term performance of grid-connected PV systems in Germany*

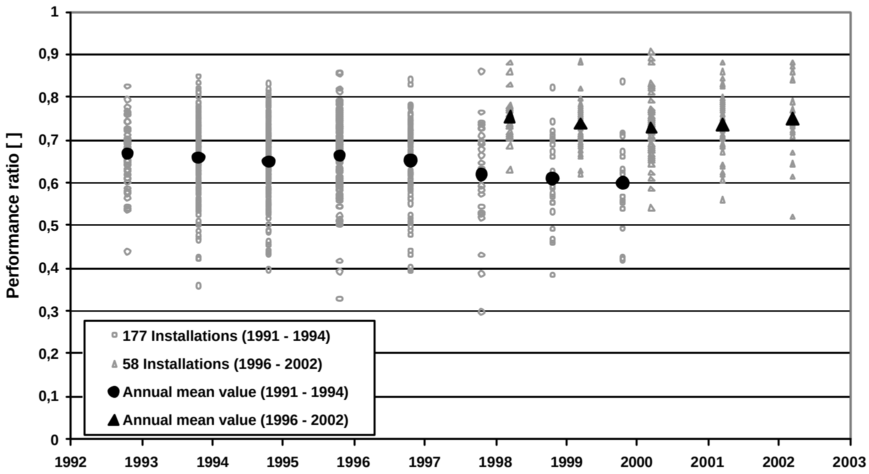


Figure 2: Trends of annual performance ratios of 177 residential PV systems installed between 1991 and 1994 compared to 58 new PV systems installed after 1996 in Germany

It can be concluded that a negative tendency in terms of performance and yields was observed for 177 early installations (1991-1994) from the rooftop programme during eight years of operation (1993-2000). Learning experiences were made for early inverter developments that had lead to frequent inverter failures, which resulted in significant reductions of the annual energy yields for some PV plants. 58 new PV installations in Germany (after 1996) revealed that they reach higher component efficiencies (e.g. inverter) and higher performance ratios (> 0.80). The high level of average annual PR (0.74) and no change of average PR in five operational years (1998-2002) indicate that the quality of the late systems in Germany has clearly increased.

### *Analysis of long-term performance of PV systems*

Task 2 has elaborated case studies on long-term performance trends, reduced yield analysis, reliability issues of PV systems and components in different countries. The final report includes summary results of the case studies and recommendations from lessons learnt and will be published in June 2004.

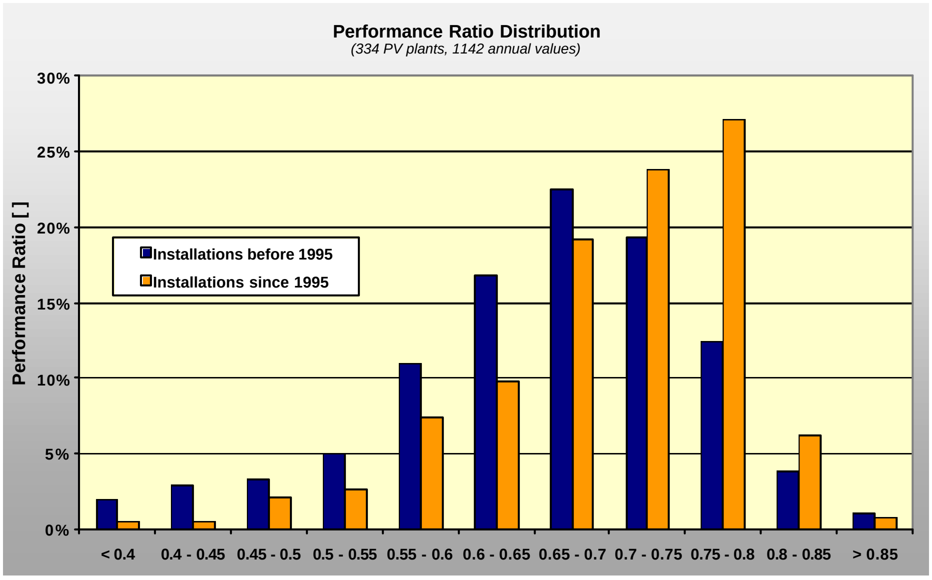


Figure 3: Distribution of annual performance ratios of 334 grid-connected PV systems (1142 annual datasets) in 11 countries for two installation periods:

a) The average annual PR of PV plants installed before 1995 is 0.65.

*b) The average annual PR of PV plants installed since 1995 is 0.70.*

As an example:

Considering 334 grid-connected PV plants in 11 countries from the Performance Database, a clear answer is given below. Figure 3 shows the distribution of 1142 annual PR values, which are grouped into two installation periods: All PV systems installed before 1995 have their maximum in the PR range of 0.65 to 0.7 and an average PR of 0.65 for 725 annual performance data. The newer installations since 1995 have their maximum in the range of 0.75 to 0.8 with an average value of PR= 0.70 for 417 annual datasets. This is a significant rise in PV system performance and reliability gained in these 11 countries during the past eight years of installation.

### *Temperature effects on PV systems performance*

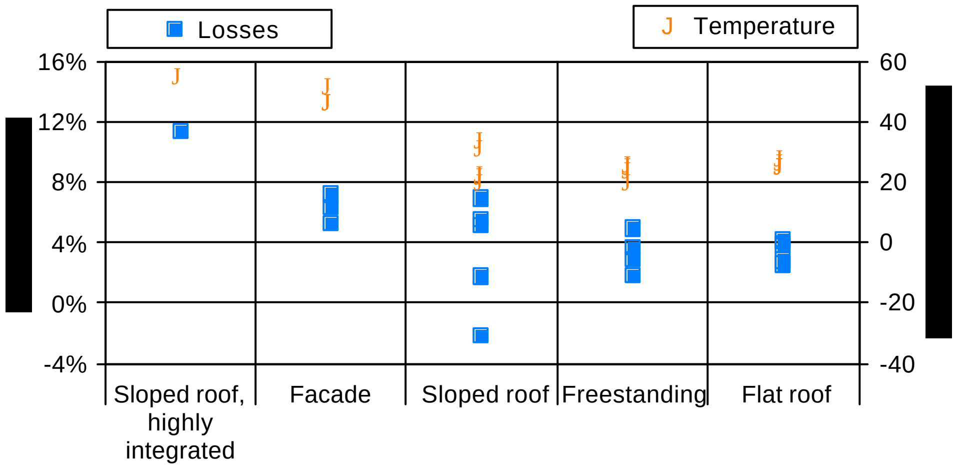


Figure 4 Overview of the results of 18 PV systems, showing the temperature losses and the rise in module temperature from ambient (K at 1000 W/m2)grouped by the type of mounting.

# Performance of PV systems under real conditions

## Results of IEA PVPS Task2
## Photovoltaic Power Systems Programme

European Workshop on Life Cycle Analysis and Recycling of Solar Modules
The “Waste” Challenge, Brussels 18/19 March 2004

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Solar Engineering Decker & Mack GmbH



# PV questions…

## and objectives of PVPS Task 2

- How reliable and longlasting are PV systems?
- What can be learnt about operational performance?
- How can the PV systems be improved?
- How to assess the operational performance?
- Which are the trends in PV system performance in different countries?

# The products of PVPS Task 2

- Technical information on operational performance, long-term reliability and sizing of PV systems and subsystems
- Network of 12 experts from 6 IEA countries
- free Database incl. the program-engine
- Reports and publications
- National and international workshops



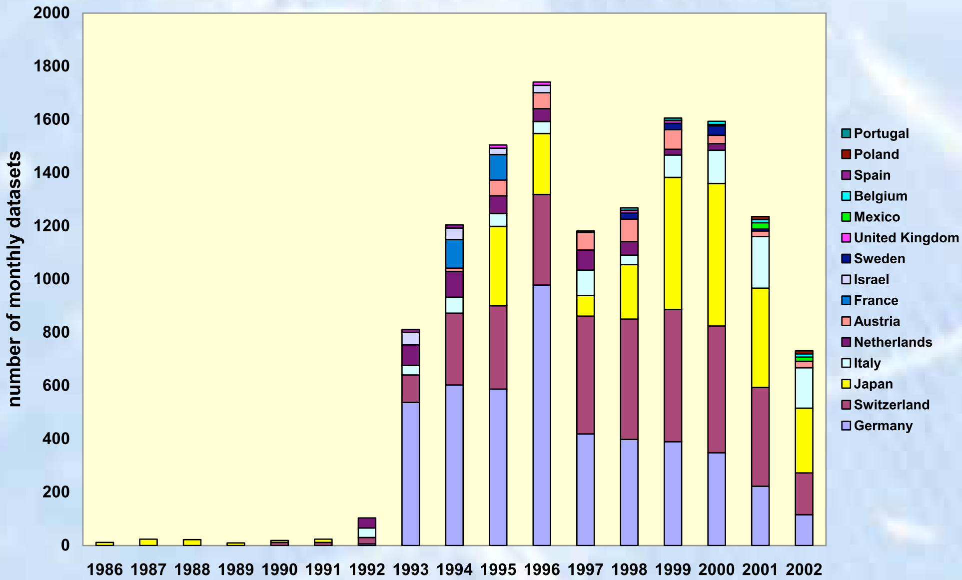
# Task 2 products

# Database contents:

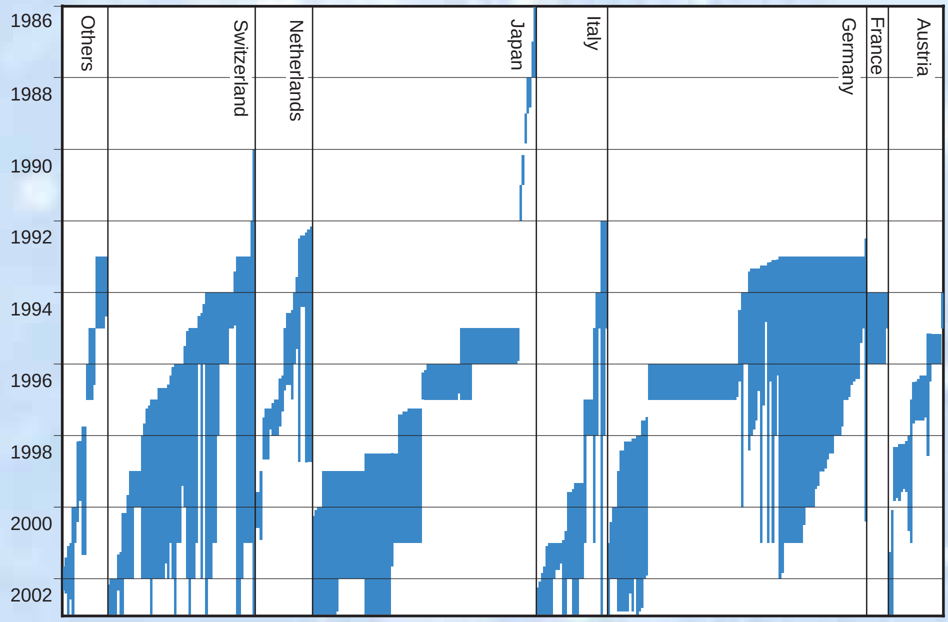
- it is free! >> www.task2.org
- Information of over 372 PV plants in IEA countries worldwide
- Grid-connected, off-grid and hybrid PV systems of 1 kWp up to 3 MWp
- General plant information
- System configuration and component data
- Monitoring data
- Calculated data



# Distribution of monitoring data



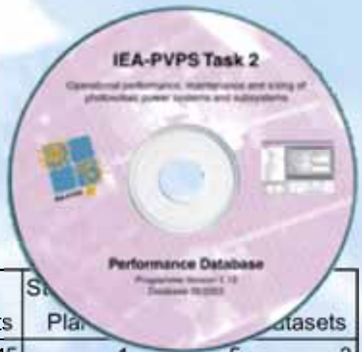
# The database footprint…





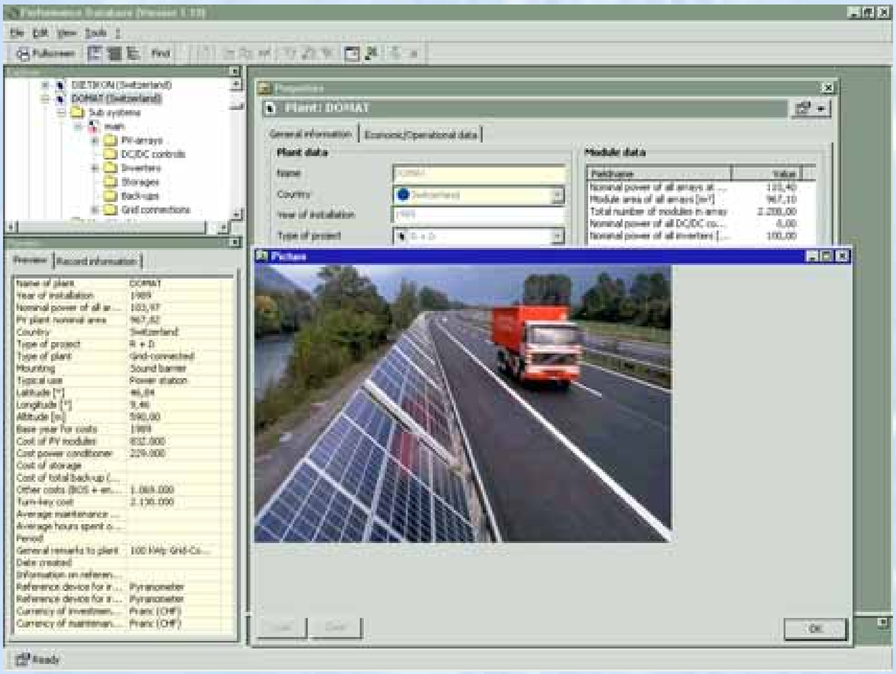

# Distribution of monitoring data

Version 05/2003




| | | | Grid connected | | | St | | |
|---|---|---|---|---|---|---|---|---|
| | Plants | Po [kWp] | Plants | Po [kWp] | Datasets | Pla | | atasets |
| Austria | 23 | 75 | 22 | 70 | 45 | 1 | 5 | 3 |
| France | 9 | 6 | | | | 9 | 6 | 17 |
| Germany | 109 | 1'291 | 108 | 1'286 | 416 | 1 | 5 | 2 |
| Italy | 30 | 5'004 | 29 | 4'933 | 81 | 1 | 71 | 3 |
| Japan | 94 | 2'671 | 82 | 1'803 | 218 | 12 | 868 | 14 |
| Netherlands | 24 | 537 | 20 | 536 | 52 | 4 | 1 | 6 |
| Switzerland | 62 | 1'964 | 62 | 1'964 | 301 | | | |
| Others | 19 | 247 | 16 | 246 | 38 | 3 | 1 | 6 |
| total | 370 | 11'796 | 339 | 10'838 | 1151 | 31 | 958 | 51 |
| Façade | | | 20 | 322 | 78 | | | |
| Stand alone | | | | | | 18 | 160 | 27 |

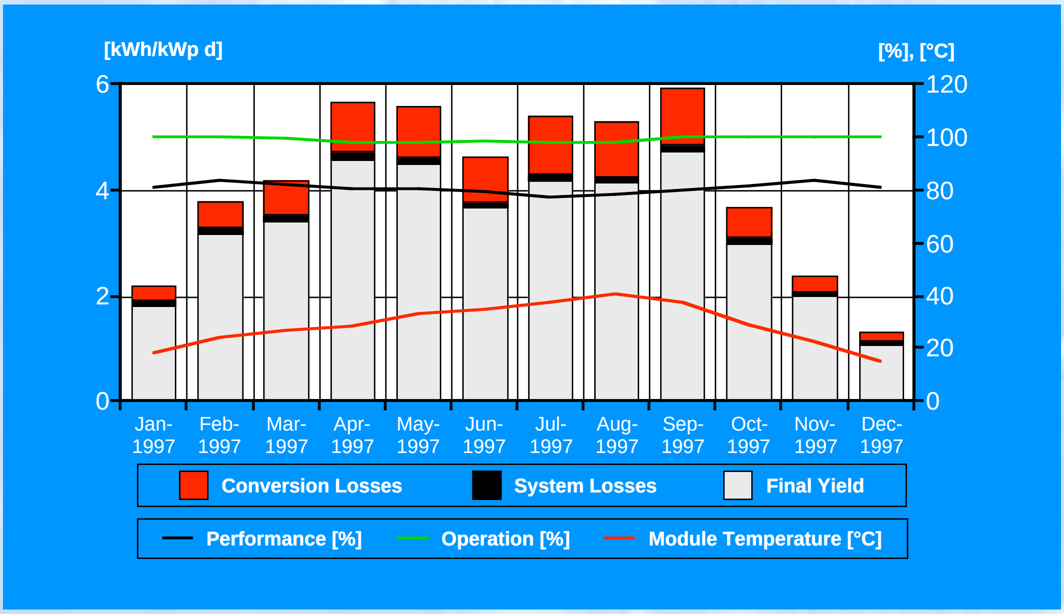
# Task 2 Performance Database



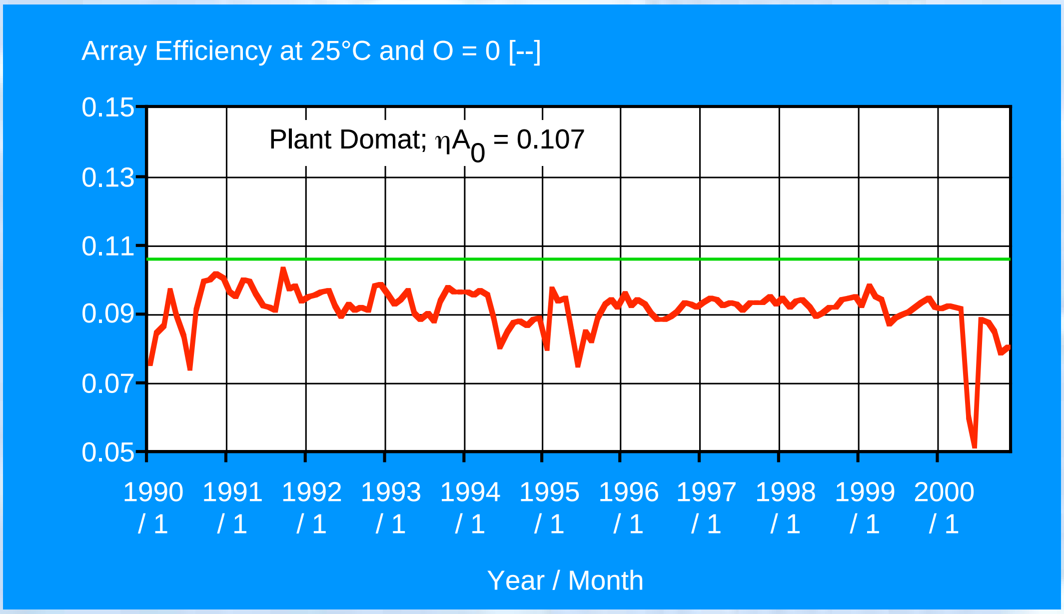



# Plant Domat, Year 1997

## PR 0.80 [--] • Yield 1'230 [kWh/kWp]



# DOMA 104 [kWp] 1990-2000;
## 1'155 [MWh] • PR 0.72 [--] • 1'010 [kWh/kWp a]






# Programme specifications


- PC of 64 MB RAM, 100 MB hard disk space
- Windows 95/98, NT4.0 or Windows 2000
- Excel for reports and data exports
- Filter, selection and easy navigation through the database
- Import and export tool

# Task 2: more activities

- Availability of irradiation data FRA
- Tools for checking the performance of PV systems
- Shading effects on PV system performance JPN
- Temperature effects on PV system performance CH
- Analysis of long-term performance and reliability of PV systems D
- Country reports on PV system performance CH

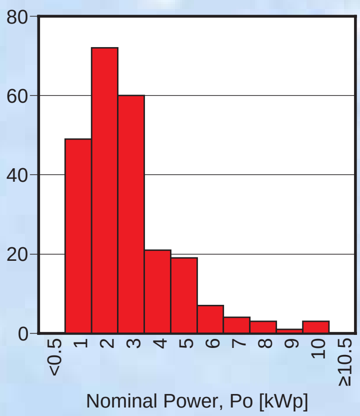


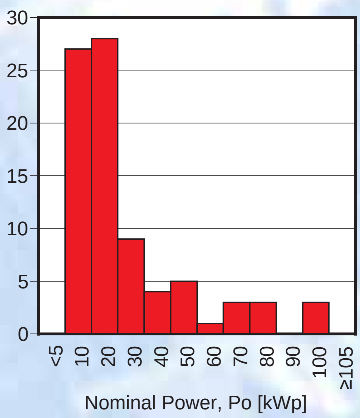
# Distribution of nominal power in database

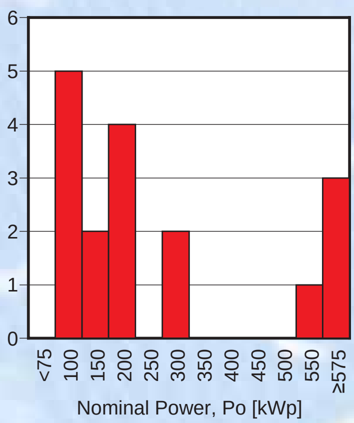
Plants < 10 kWp

Plants 10 - 99 kWp

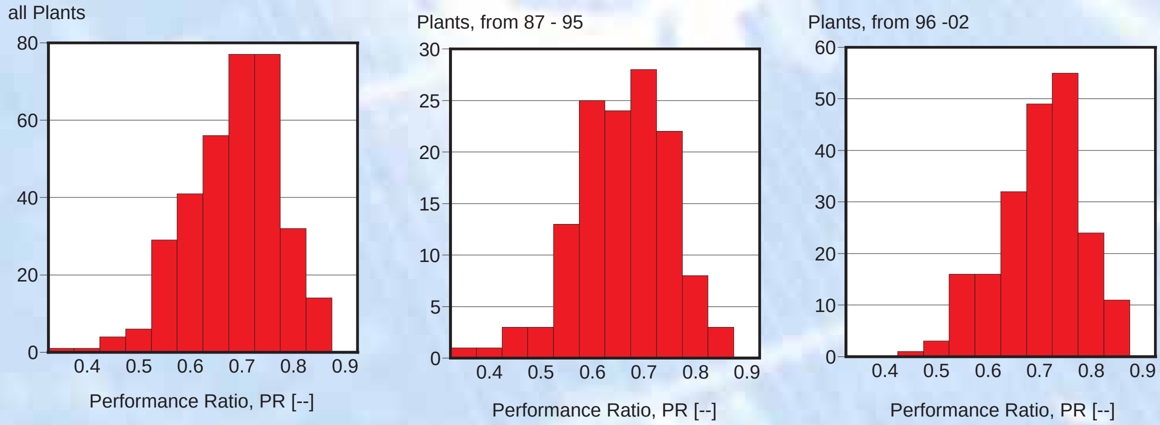
Plants > 100 kWp



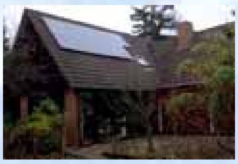
# Histograms of annual performance ratio






# 1000-Roofs-PV-Programme in Germany





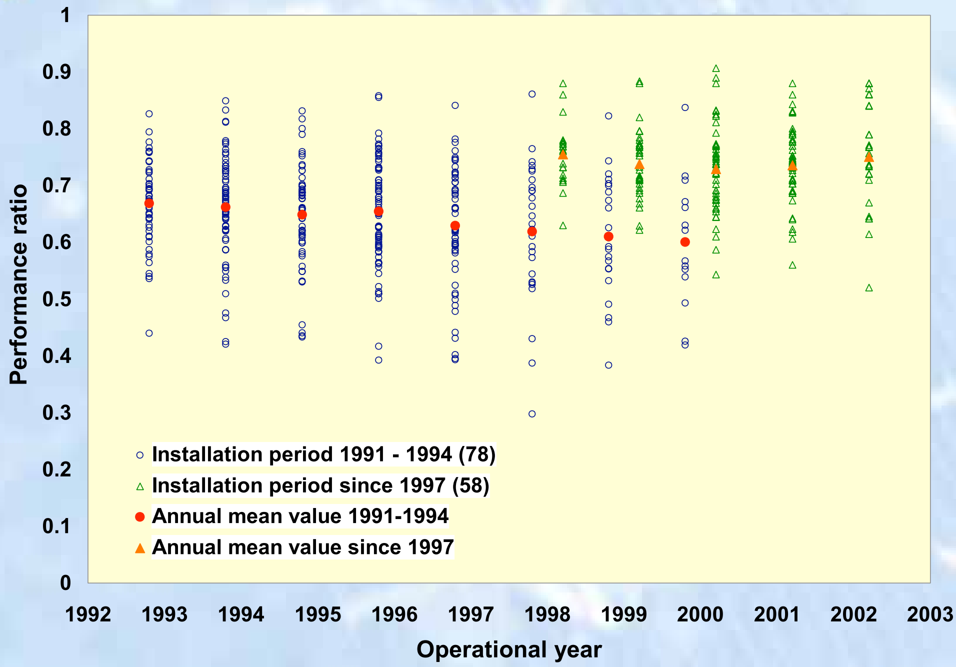




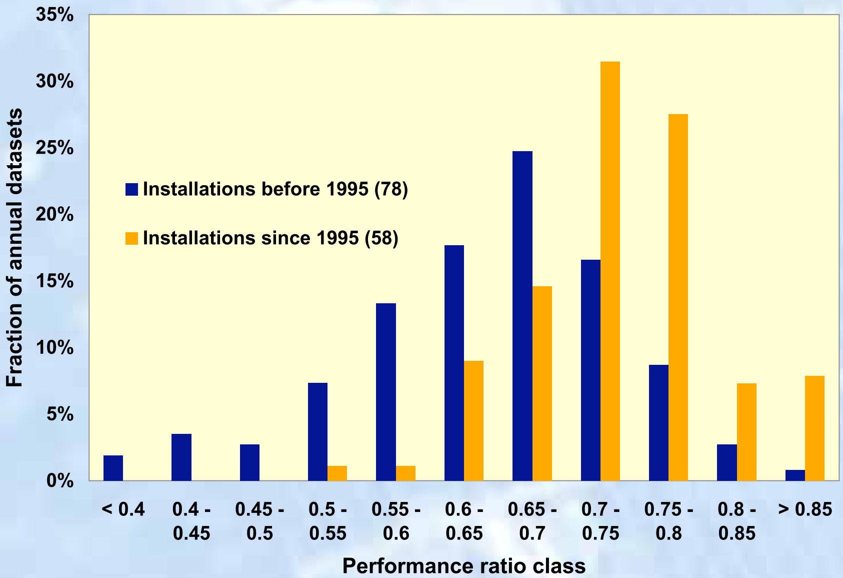
# Germany (new installations)



# Germany – PV system performance



# Germany – PV system performance




Before 1995: avr PR = 0.64; since 1995: avr. PR = 0.74



# PV systems in Switzerland

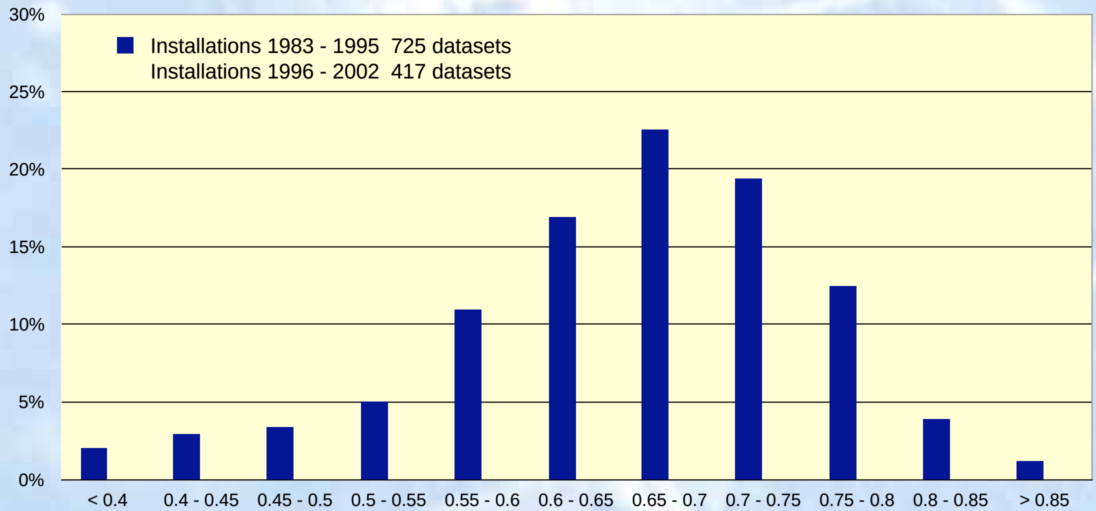
# PV systems in Japan

IEA International Energy Agency Photovoltaic Power Systems Programme - Task 2 TNO



# Trends in PV system performance

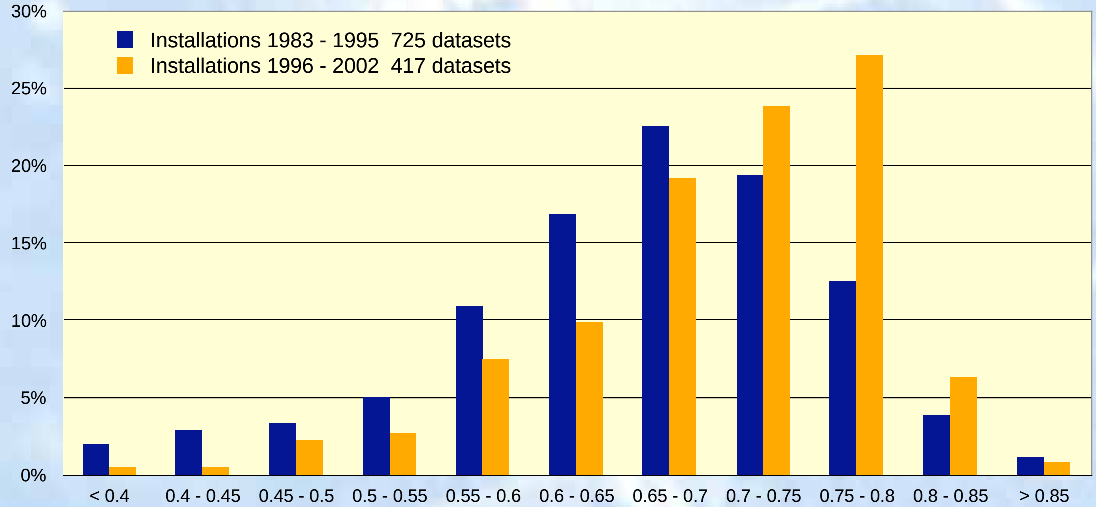
## 334 PV systems from 14 countries; 1142 annual datasets




IEA International Energy Agency Photovoltaic Power Systems Programme - Task 2 TNO

# Trends in PV system performance

## 334 PV systems from 14 countries; 1142 annual datasets

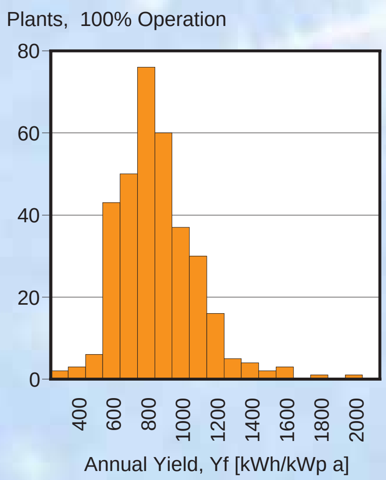


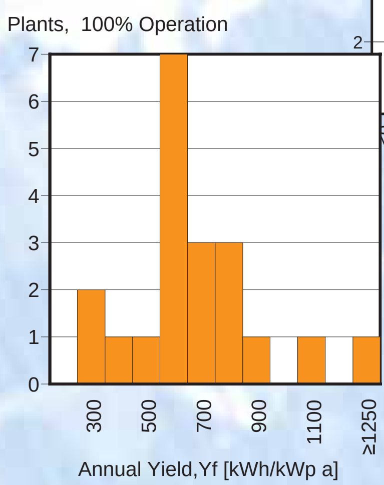

Annual mean PR: 1983 - 1995 = 0.66 1996 - 2002 = 0.70



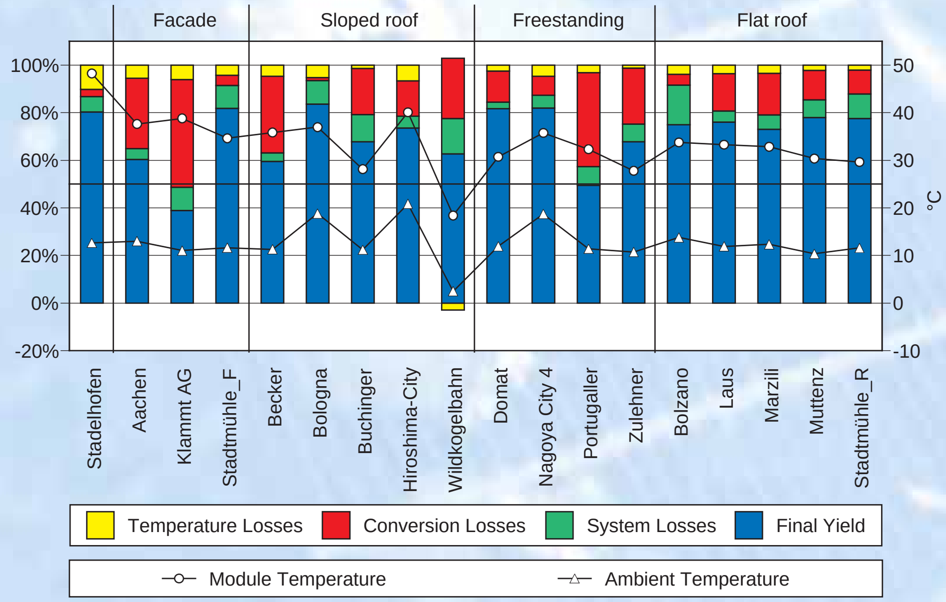
# all plants (370x) vs facade (21x)

## Yield Yf [kWh/kWp a]



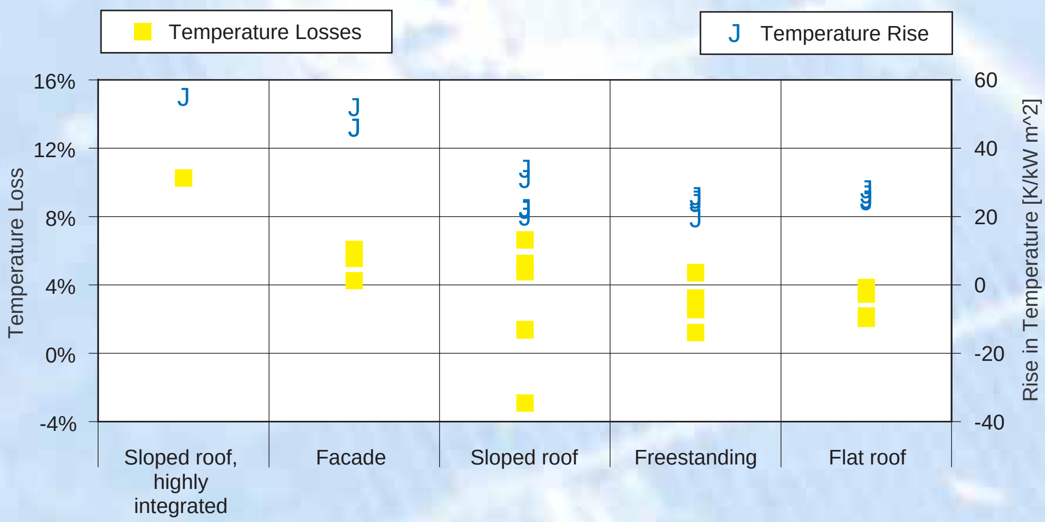




# Temperature effects on PV system performance I



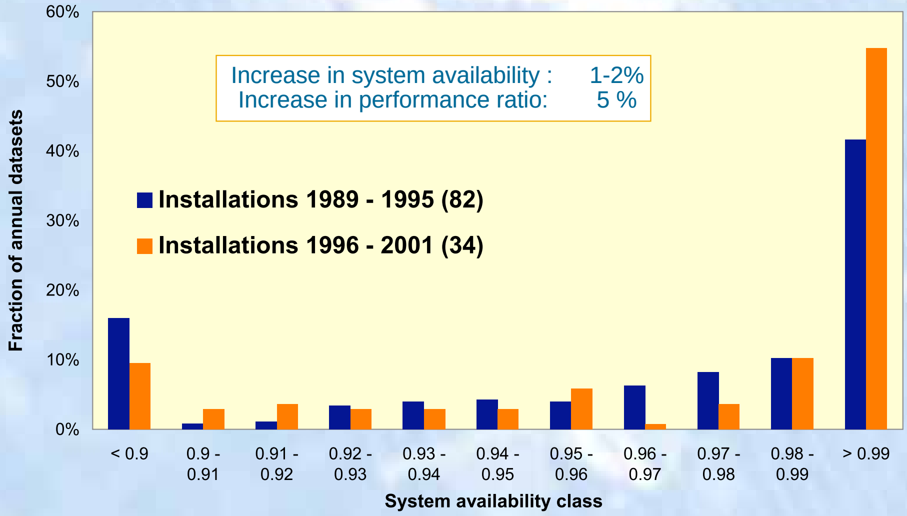



# Temperature effects on PV system performance II



# Trends of reliability

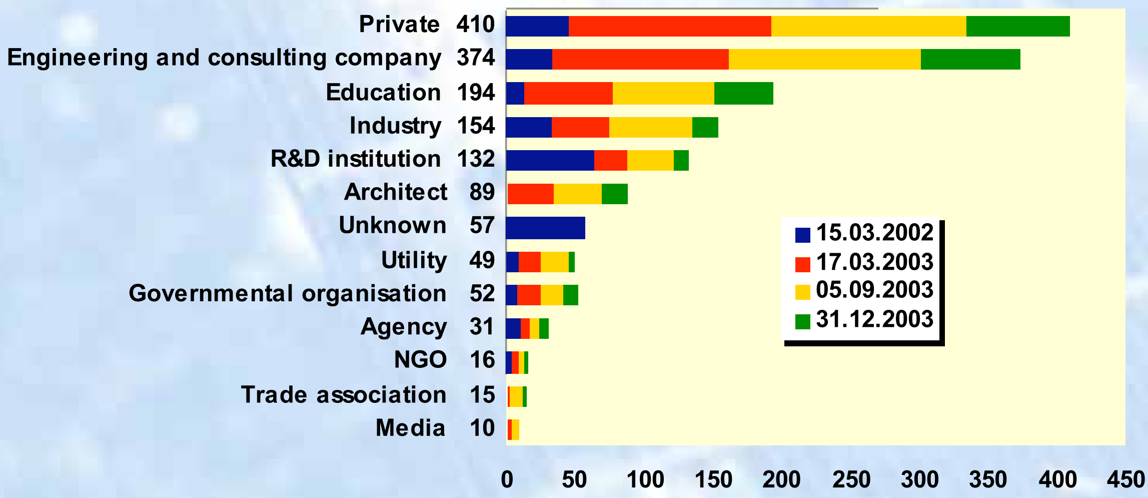
## of 116 systems in Germany, Switzerland and Italy




IEA International Energy Agency Photovoltaic Power Systems Programme - Task 2 TNO



# Distribution of PV database by user




IEA International Energy Agency Photovoltaic Power Systems Programme - Task 2 TNO

# IEA PVPS planed activity

from Proposed workplan for Task 2 extension

2004 - 2007

- Activity 34: Life cycle economical performance «putting the elements together»
- Evaluate the existing information of systems in the task 2 database, concerning long-term electrical performance. Include a simple model of capital cost typical for the different sizes and markets (interest, pay back time etc.).



# Expected output:

- Technical report
  "The elements of life circle economic performance for photovoltaic installations" (working title).
- Workshop
- Findings of the activity are summarized in a concluding report.

## Lessons learned

- Clear tendency of increasing performance for new PV installations
- Range of PR distribution is decreasing. Broad range is due to failures, shading, MPPT mismatch, badly oriented arrays and high module temperatures.
- Well-performing system show PR>0.80, while mean PR of 0.70 is lower than expected.
- Early installations show decreasing PR tendency; new PV plants have no change in annual PR.
- Rise in system performance is only partly due to rise in system availability.



## Conclusions

- Performance trends are clearly positive. Average annual PR values of 0.80 are to be achieved.
- Same problems & same recommendations to be given for systems of lower performance
- BIPV must combine building requirements, architectural design criteria and highest technical performance.
- Long-term experiences in reliabilities of PV systems and components are important for a wide dissemination of PV in future.
- Monitoring activities and programmes are required to ensure quality management and will lead to improved system reliability.

## Recommendations

- Consider reliability of inverters and allow for easy replacement of faulty units.
- Avoid long repair times of faulty components
- Minimize shading by array wiring configuration
- Ensure that orientation of PV array is optimized
- Avoid arrays with different orientations feeding into one inverter (MPPT mismatch)
- Prevent overheating of PV modules
- Understand factors that affect PR: deviation from module specifications, reflection losses, module mismatch in strings, wiring losses.



# External costs of photovoltaics: What is it based on?

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## The *NetherlandsExternE study (http://www.externe.info/)*

The main aim of the ExternE research projects (European Commission, Directorate-General for Research, 2003; European Commission, Directorate-General for Science, Research and Development (DG-XII), 1999; IER, 1997) was to develop a methodology to calculate the external costs caused by energy production and consumption. External costs are defined as the monetary quantification of the socio-environmental damage, expressed in eurocents per kWh. As such, it can provide a scientific basis for policy decisions and legislative proposals like subsidizing cleaner technologies and energy taxes to "internalize" the external costs.

### *ExternE 2003 brochure*

The ExternE 2003 brochure (European Commission, Directorate-General for Research, 2003) gives the impression that electricity production from photovoltaics leads to a greater health damage than the electricity production from gas or nuclear power. Some views about this study were already discussed by (Nickel, 2004).

### *Aim*

The external cost figures for electricity production in the EU and in Germany, given in the ExternE 2003 brochure, are given without references, so it is not clear on which information it is based. This paper aims to retrieve the input data that was used for the calculation of the external costs of photovoltaic systems. Apparently, the two tables "External cost figures for electricity production in the EU for existing technologies" and "Quantified marginal external costs of electricity production in Germany" are based on different calculations. For example the sum of external costs for the different technologies given in the first table are not equal to the values presented in the second.

### *ExternE data for PV (1): the Kaspar 1995 study*

The determination of the external costs of photovoltaics in the upper table in the ExternE 2003 brochure and in (European Commission, Directorate-General for Science, Research and Development (DG-XII), 1999; IER, 1997) are based on only two case studies in only one country, namely Germany. The data are compiled by ISET (Kaspar, 1995) and taken from the 1000 roof program. One case is a 4.8 kWp roof system of 96 polycrystalline silicon PV modules produced by DASA/AEG in 1990 and located in Emstal-Riede with a performance of 730 kWh/y per kWp. The other case is a 13 kWp façade system of 200 frameless polycrystalline modules produced by DASA and located in Bielefeld with an estimated performance of 630 kWh/y per kWp. Material and energy use of 3 inverters, special cabling and measurement systems were not taken into account. The expected lifetime is 25 years. The burdens were quantified using Life Cycle Inventory data of (Hagedorn, 1992), representing technologies from the late eighties of German companies.

### *ExternE data for PV (2): the Hartmann 2001 study*

The external costs of photovoltaics given in the lower table of the ExternE 2003 brochure are very similar to the values in table 4 of (Voß, 2000). In (Voß, 2000) the total life cycle emission of $CO_2$-equivalents is **216 g/kWh** for PV for an amorphous silicon PV-home application of 5 kWp. Voß states that this generation technology is "representative for current and near-future technologies operated in Germany". No reference is given to the study on which this is based.

In table 6-8 of the PhD thesis of (Hartmann, 2001), published in the same group of Voß, the Institute of Energy Economics and the Rational Use for Energy (IER) of the University of Stuttgart, the same value of **215 g/kWh** is given for an ***amorphous silicon 5 kWp system, of which 10.5% is for a backup system (assuming PV is 10% of the electricity mix)***. So we conclude that the PV data in the lower table in the ExternE 2003 brochure are based on this thesis.

### *Discussion*

A citation from pages 89-90 of this thesis (Hartmann, 2001) is "Die Massen- und Energiemengen entsprechen dem aktuellen Stand der Technik (vgl. 'worst-case Daten' in /v. Engelenburg; Alsema 1994/)."

The *worst-case* amorphous silicon data of (Engelenburg, 1993) are data from *mid 80's* and are *not* representative of current or near-future values. Amorphous silicon is not a representative technology. In Europe in 2002 92% of the cell/module production was crystalline silicon and only 8% was amorphous silicon (Maycock, 2003). Furthermore, PV is currently only a very small part of the German electricity mix, so no backup system is necessary.

Using more recent data of (Alsema, 2003) and assuming a valuation of 19 euro per ton of $CO_2$, the external cost for global warming will decrease the ExternE 2003 value of 0.33 eurocents per kWh to:

- 0.21 eurocents per kWh for standard/BOAL multicrystalline silicon roof PV system located in the Netherlands,
- 0.12 eurocents per kWh for standard/BOAL multicrystalline silicon roof PV system located in South-Europe,
- 0.09 eurocents per kWh for a future RGS/PV wire free multicrystalline silicon roof PV system located in the Netherlands and 0.05 eurocents per kWh for a future RGS/PV wire free multicrystalline silicon roof PV system located in South Europe.

The new valuation of all other emissions will soon be available as a result of the NewExt project and total damage costs will be calculated.

### *Conclusions*

The aim of the ExternE study was to provide a scientific basis for the external cost calculations, but the lack of referencing and not disclosing the fact that the figures in the

ExternE 2003 brochure are based on ancient PV technology, is not an example of good scientific practice.

We are looking forward to the publication of the results of new calculations, which will be conducted in the ExternE-Pol project using LCA emission data described in the new EcoInvent2000 database (Jungbluth, 2003).
Other countries than Germany must be included, since the performance of the PV systems is highly dependent on location (solar irradiation).

### References


Alsema,E. (2003): *Duurzaamheid van fotovoltaïsche systemen op basis van geavanceerde silicium technologie;* Utrecht University, the Netherlands, 90-393-3581-8, **NWS-E-2003-17: -51 p.;** http://www.chem.uu.nl/nws/www/publica/sci2003.htm

Engelenburg,B.C.W.v. and E.A.Alsema (1993): *Environmental aspects and risks of amorphous silicon solar cells;* Utrecht University, Utrecht, the Netherlands, **93008: -65 p.**

European Commission, Directorate-General for Research (2003): *External costs. Research results on socio-environmental damages due to electricity and transport;* Office for Official Publications of the European Communities, Luxembourg, 92-894-3353-1, **EUR 20198: -24 p.;** http://europa.eu.int/comm/research/energy/pdf/externe_en.pdf

European Commission, Directorate-General for Science, Research and Development (DG-XII) (1999): *ExternE : externalities of energy : vol. 10 : National implementation;* CIEMAT, Office for Official Publications of the European Communities, Luxembourg, 92-828-3723-8, **EUR-18528: -606 p.**

Hagedorn,G. and E.Hellriegel (1992): *Umweltrelevante Masseneinträge bei der Herstellung verschiedener Solarzellentypen; eine vergleichende Analyse konventioneller und ausgewählter neuer Verfahren unter Berücksichtigung der Einsatzstoffe und Prozeßketten sowie der Entsorgungs- und Recyclingmöglichkeiten - Endbericht - Teil I: Konventionelle Verfahren;* Forschungsstelle für Energiewirtschaft (FfE), München, Germany, **051.24: -220 p.**

Hartmann,D. (2001): *Ganzheitliche Bilanzierung der Stromerzeugung aus regenerativen Energien (Band 83);* PhD thesis, **IER, Germany, 0938-1228**; -188 p.**;** mailto:hildegard.euler-hutflesz@ier.uni-stuttgart.de

IER (1997): *ExternE National Implementation Germany;* http://externe.jrc.es/ger.pdf

Jungbluth,N. (2003): *Photovoltaik;* ***Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. Final report ecoinvent 2000 No. 6-XII,*** **Paul Scherrer Institute Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland,** http://www.ecoinvent.ch/

Kaspar,F., F.Raptis and J.Sachau (1995): *Assessment of the external costs of the photovoltaic and wind energy life cycle - National implementation in Germany. Final report - extended version- prepared for the Commission of the European Union DG XII in the frame of the contract JOU2-CT-0264;* Institut für Solare Energieversorgungstechnik (ISET), Kassel, Germany, http://www.iset.de

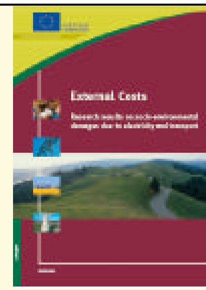
Maycock, P.D. (2003): **PV News 22/3**, http://www.pvenergy.com/.

Nickel,J. (2004): *A new EU study with old data: PV unhealthier than nuclear power. Quite irritated*.; **Photon International 1: 18-19**

Voß,A. (2000): *Sustainable Energy Provision: A comparative assessment of the various electricity supply options;* **Proceedings of the SFEN Conference "What Energy for Tomorrow?", Strasbourg, 27-29 November 2000 , 19-27**

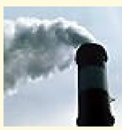
# ExterE - External costs of PV

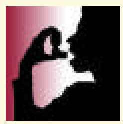
## What is it based on?




Mariska de Wild-Scholten

Energy research Centre of the Netherlands







# Outline

- ExternE 2003 brochure
- ExternE project series
- ExternE methodology
- **aim:** ExternE data for PV1 & PV2
- ExternE current activities
- New external costs for global warming
- Conclusions

# ExternE 2003 brochure: PV1
# damage costs of electricity production

**External cost figures for electricity production in the EU for existing technologies[1] (in € cent per kWh*)**

| Country | Coal & lignite | Peat | Oil | Gas | Nuclear | Biomass | Hydro | PV | Wind |
|---|---|---|---|---|---|---|---|---|---|
| AT | | | | 1-3 | | 2-3 | 0.1 | | |
| BE | 4-15 | | | 1-2 | 0.5 | | | | |
| DE | 3-6 | | 5-8 | 1-2 | 0.2 | 3 | < | 0.6 | 0.05 |
| DK | 4-7 | | | 2-3 | | 1 | | | 0.1 |
| ES | 5-8 | | | 1-2 | | 3-5** | | | 0.2 |
| FI | 2-4 | 2-5 | | | | 1 | | | |
| FR | 7-10 | | 8-11 | 2-4 | 0.3 | 1 | 1 | | |
| GR | 5-8 | | 3-5 | 1 | | 0-0.8 | 1 | | 0.25 |
| IE | 6-8 | 3-4 | | | | | | | |
| IT | | | 3-6 | 2-3 | | | 0.3 | | |
| NL | 3-4 | | | 1-2 | 0.7 | 0.5 | | | |
| NO | | | | 1-2 | | 0.2 | 0.2 | | 0-0.25 |
| PT | 4-7 | | | 1-2 | | 1-2 | 0.03 | | |
| SE | 2-4 | | | | | 0.3 | 0-0.7 | | |
| UK | 4-7 | | 3-5 | 1-2 | 0.25 | 1 | | | 0.15 |

* sub-total of quantifiable externalities (such as global warming, public health, occupational health, material damage)
** biomass co-fired with lignites

Source: http://www.externe.info/externpr.pdf




# ExternE 2003 brochure: PV2

**Quantified marginal external costs of electricity production in Germany[2] (in € cent per kWh)**

| | Coal | Lignite | Gas | Nuclear | PV | Wind | Hydro |
|---|---|---|---|---|---|---|---|
| *Damage costs* | | | | | | | |
| Noise | 0 | 0 | 0 | 0 | 0 | 0.005 | 0 |
| Health | 0.73 | 0.99 | 0.34 | 0.17 < | 0.45 | 0.072 | 0.051 |
| Material | 0.015 | 0.020 | 0.007 | 0.002 | 0.012 | 0.002 | 0.001 |
| Crops | 0 | 0 | 0 | 0.0008 | 0 | 0.0007 | 0.0002 |
| Total | 0.75 | 1.01 | 0.35 | 0.17 | 0.46 | 0.08 | 0.05 |
| *Avoidance costs* | | | | | | | |
| Ecosystems | 0.20 | 0.78 | 0.04 | 0.05 | 0.04 | 0.04 | 0.03 |
| Global Warming | 1.60 | 2.00 | 0.73 | 0.03 < | 0.33 | 0.04 | 0.03 |
| **TOTALS** | 2.55 | 3.79 | **1.12** | **0.25** | **0.83** | 0.16 | 0.11 |

[2] *Median estimates; current technologies; $CO_2$ emissions are valued with avoidance costs of € 19 per ton of $CO_2$*

Source: http://www.externe.info/externpr.pdf

# ExternE 2003 brochure: PV1 damage costs of electricity production

**EXTERNAL COST FIGURES FOR ELECTRICITY PRODUCTION IN THE EU FOR EXISTING TECHNOLOGIES[1] (IN € CENT PER KWH*)**

| Country | Coal & lignite | Peat | Oil | Gas | Nuclear | Biomass | Hydro | PV | Wind |
|---|---|---|---|---|---|---|---|---|---|
| AT | | | | 1-3 | | 2-3 | 0.1 | | |
| BE | 4-15 | | | 1-2 | 0.5 | | | | |
| DE | 3-6 | | 5-8 | 1-2 | 0.2 | 3 | | | 0.05 |
| | | | | | | | | **0.6** | |
| | **2.55-3.79** | **--** | **--** | **1.12** | **0.25** | **--** | **0.11** | **0.83** | **0.16** |
| FI | 2-4 | 2-5 | | | | 1 | | | |
| FR | 7-10 | | 8-11 | 2-4 | 0.3 | 1 | 1 | | |
| GR | 5-8 | | 3-5 | 1 | | 0-0.8 | 1 | | 0.25 |
| IE | 6-8 | 3-4 | | | | | | | |
| IT | | | 3-6 | 2-3 | | | 0.3 | | |
| NL | 3-4 | | | 1-2 | 0.7 | 0.5 | | | |
| NO | | | | 1-2 | | 0.2 | 0.2 | | 0-0.25 |
| PT | 4-7 | | | 1-2 | | 1-2 | 0.03 | | |
| SE | 2-4 | | | | | 0.3 | 0-0.7 | | |
| UK | 4-7 | | 3-5 | 1-2 | 0.25 | 1 | | | 0.15 |

* sub-total of quantifiable externalities (such as global warming, public health, occupational health, material damage)
** biomass co-fired with lignites

Source: http://www.externe.info/externpr.pdf



# ExternE project

- <u>Goal:</u> development of methodology to determine the external costs caused by energy production and consumption
- <u>External costs</u> = monetary quantification of socio-environmental damage (eurocents / kWh)
- <u>Damages assessed</u> from cradle to grave:
  human health, building materials, crops, amenity losses (due to noise), ecosystem (acidification & eutrophication), global warming
- Provide <u>scientific basis</u> for
  policy decisions & legislative proposals:
  - subsidise cleaner technologies
  - energy tax: "internalising" external costs
  - objective to reduce greenhouse gases emission

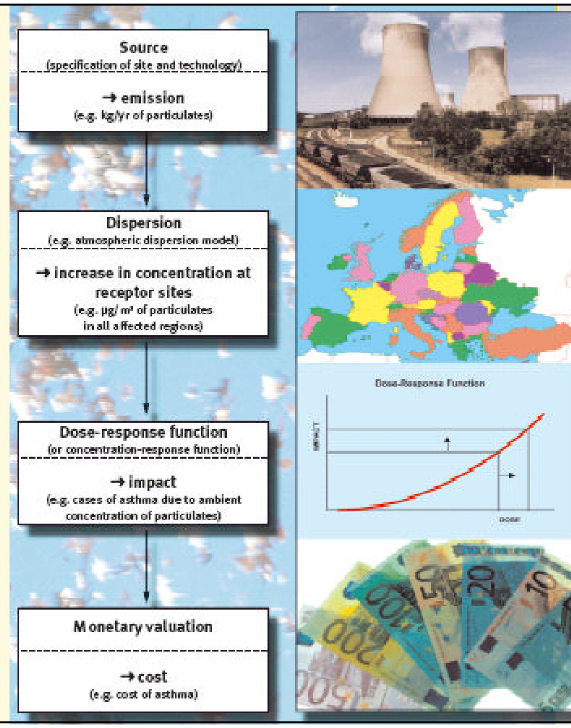
*Source: http://www.externe.info/ & http://externe.jrc.es/*

# ExternE methodology

Impact pathway approach
(EcoSense model)

is site specific

Source:
http://europa.eu.int/comm/research/energy/pdf/externe_en.pdf






# ExternE methodology (2)

**LCA**

↓

**Emissions (kg/kWh)**

**ExternE**

↓

**Cost/impact (euro/kg)**

**External cost (euro/kWh)**

# ExternE data for PV1:

## the Kaspar 1995 study (1)

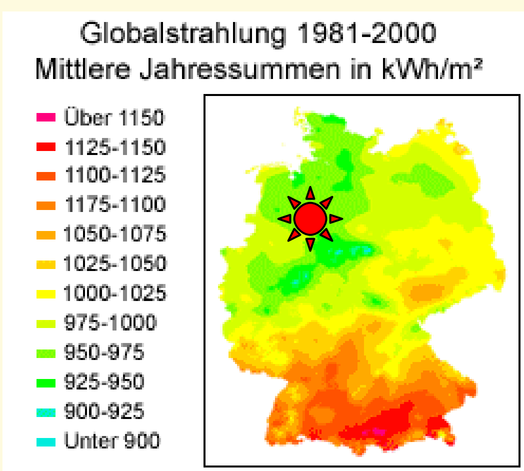
| Location | Technology | Power ($kW_p$) | PV energy production (kWh/y) |
|---|---|---|---|
| Emstal-Riede (Germany) | 96 polycrystalline PV modules on roof DASA/AEG 1990 | 4.8 | 3494 in 1993 (measured) ➔ 0.73 kWh/y per $W_p$ |
| Bielefeld (Germany) | 200 frameless polycrystalline modules in façade DASA | 13 | 8200 in 1990 (estimated!) ➔ 0.63 kWh/y per $W_p$ |

- Material and energy use of 3 inverters, special cabling and measurement systems not taken into account
- Expected life time = 25 years



# ExternE data for PV1:

## the Kaspar 1995 study (2)




Bielefeld
Bad Emstal-Riede

*Source: http://www.solarserver.de/lexikon/sonneneinstrahlung-e.html*

# ExternE data for PV1:
## the Kaspar 1995 study (3)

quantification of burdens during life cycle:

using data of Hagedorn/Hellriegel (1992)
Technology <1991
German companies

Source: Hagedorn,G. and E.Hellriegel (1992): *Umweltrelevante Masseneinträge bei der Herstellung verschiedener Solarzellentypen; eine vergleichende Analyse konventioneller und ausgewählter neuer Verfahren unter Berücksichtigung der Einsatzstoffe und Prozeßketten sowie der Entsorgungs- und Recyclingmöglichkeiten - Endbericht - Teil I: Konventionelle Verfahren*; Forschungsstelle für Energiewirtschaft (FfE), München, Germany, **051.24: -220 p.**



# ExternE data for PV2:
## Voß 2000

| euro-cent / kWh | Coal | Lignite | Gas CC | Nuclear | PV | Wind | Hydro |
|---|---|---|---|---|---|---|---|
| **Health effects** | 0.8 | 1.0 | 0.3 | 0.2 | 0.4 | 0.05 | 0.04 |
| **Crop losses** | -0.03 | -0.03 | -0.01 | 0.0008 | -0.003 | 0.0005 | 0.0004 |
| **Material damage** | 0.02 | 0.02 | 0.007 | 0.002 | 0.01 | 0.001 | 0.0007 |
| **Noise nuisance** | | | | | | 0.006 | |
| **Acidification/eutrophication** | 0.2 | 0.8 | 0.04 | 0,00 | 0.04 | 0,00 | 0,00 |
| **Global warming** | 1.6 | 2,00 | 0.8 | 0.03 | 0.3 | 0.03 | 0.03 |
| **Sub-total** | **2.6** | **3.8** | **1.1** | **0.2** | **0.8** | **0.09** | **0.07** |

Table in ExternE 2003 brochure is similar to this one.

*Source: Voß, A. (2000) Sustainable Energy Provision:* ***A comparative assessment of the various electricity supply options****; Proceedings of the SFEN Conference "What Energy for Tomorrow?" , Strasbourg, 27-29 November 2000, 19-27.*

# ExternE data for PV2:
## Voß 2000

- amorphous silicon PV-home application of 5 kWp, stating that this generation technology is "representative for current and near-future technologies operating in Germany".
- Conclusion: "If the world is serious about decarbonising the global energy economy, nuclear power - despite distinct political difficulties - may become increasingly attractive again in the next decades".
- No reference is given for entries in table.

**216 $CO_2$ eq / kWh**

*Source: Voß, A. (2000) Sustainable Energy Provision: A comparative assessment of the various electricity supply options; Proceedings of the SFEN Conference "What Energy for Tomorrow?" , Strasbourg, 27-29 November 2000, 19-27.*



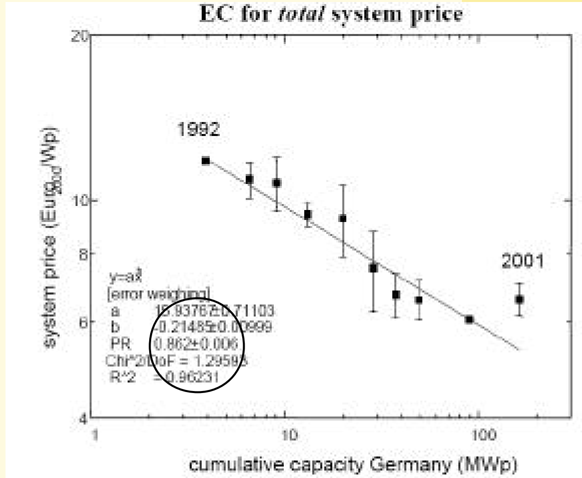
# ExternE data for PV2:
## the Hartmann 2001 PhD thesis

**215 $CO_2$ eq / kWh**

- amorphous silicon 5 kWp system, of which 10.5% is for a backup system (assuming PV is 10% of the electricity mix)
- using worst case a-Si data of Engelenburg & Alsema (1993), using data of Hagedorn et al. (1989)

*Sources: Hartmann, D. (2001) Ganzheitliche Bilanzierung der Stromerzeugung aus regeneratieven Energien (Band 83); PhD thesis, IER, Germany, 0938-1228: table 6-8.*
*Engelenburg,B.C.W.v. and E.A.Alsema (1993): Environmental aspects and risks of amorphous silicon solar cells; Utrecht University, Utrecht, the Netherlands,* ***93008: -65 p.***
***Hagedorn,G., S.Lichtenberg and H.Kuhn (1989): Cumulative energy consumption for the production of solar cells and photovoltaic power systems (in German); KFA Jülich GmbH, Jülich, Germany,***

# Experience curve for PV system




**Source: Alsema,E.A. (2003):** ***PV cost and development. PV experience curves from the Photex database;*** **PHOTovoltaic systems and EXperience curves, PV experts Workshop, 4 June 2003 ; http://www.energytransition.info/photex/docs/ws-br040603ea.pdf**



# New external costs for global warming

## 19 euro / ton $CO_2$

**ExternE 2003** brochure (lower table):

- 0.33 eurocents / kWh

**Alsema 2003**:

- 0.21 eurocents / kWh standard/BOAL multi-Si in NL
- 0.12 eurocents / kWh standard/BOAL multi-Si in South Europe
- 0.09 eurocents / kWh RGS/PV wire-free multi-Si in NL
- 0.05 eurocents / kWh RGS/PV wire-free multi-Si in South Europe

*Sources: http://www.externe.info/externpr.pdf &*
*Alsema,E. (2003): Duurzaamheid van fotovoltaïsche systemen op basis van geavanceerde silicium technologie; Utrecht University, the Netherlands, 90-393-3581-8,* ***NWS-E-2003-17: -51 p.;***

# ExternE: current activities

**NewExt** project

- development of the methodology
- project coordination by Rainer Friedrich (IER, Stuttgart)

**ExternE-Pol** project

- new calculations using EcoInvent2000 LCI database
- project coordination by Ari Rabl (ARMINES/Ecoles des Mines, Paris)

*http://www.ier.uni-stuttgart.de/ http://www.arirabl.com/ http://www.ecoinvent.ch/*



ECN

# Conclusions

**ExternE 2003 brochure**:

- Lack of referencing.
- The fact that data of technologies of late 80's are used is not disclosed.
- Table will be used by others to compare energy production technologies (see Voß 2000).

**Recommendations**:

- New calculations (including PV systems from other countries) + new publication
- PV industry: supply new data for LCA



ECN

# The 'ExternE' Methodology to Assess External Costs of Energy Conversion and Some Results on External Costs of PV and other Electricity Generating Techniques

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The production and application of technologies, for example for energy conversion or transport of passengers and goods, cause considerable damage to human health, flora and fauna, ecosystems and materials. These impacts are mostly externalities, i.e. not reflected in the prices of goods. This damage however should be considered in the framework of technology assessments and when taking decisions that have an impact on the amount of emissions to the air. A direct way to do this is the quantification of the damage and the subsequent transformation into monetary units based on the 'willingness-to-pay-approach'. The resulting external costs can then be internalised via taxes or charges, used for cost-benefit-analyses, for the identification of weak points of a technology or as an indicator for environmental damage within green accounting.

In recent years there has been progress in the development of a methodology for assessing external costs thanks to a series of projects financed by the European Commission, DG Research, called ExternE (European Commission 1999a-d) and (Friedrich and Bickel 2001), the latest phase –the project NewExt– has just ended. This paper presents an overview of the methodology and presents some results.

It should be emphasized, that external costs are technology and site dependent. Thus a fixed value for the external costs for a category of techniques (say PV) does not exist. Consequently, ExternE does not provide figures, but a methodology to generate figures. For concrete applications the methodology should be used to calculate adequate external costs with input data according to the concrete decision situation.Existing results can thus only give some hints on the order of magnitude and the structure and feature of external cost data.

## *The Impact Pathway Approach*

The ExternE Project has adopted the 'impact pathway' approach for the assessment of the external impacts and associated costs resulting from the supply and use of energy. The phrase 'impact pathway' simply relates to the sequence of events linking a 'burden' to an 'impact' and subsequent valuation. The methodology therefore proceeds sequentially through the pathway, as shown in Fig 1. The chain of causal relationships starts from the emission of a burden through transport and chemical conversion in the environment to the impacts on various receptors, such as human beings, crops, building materials or ecosystems. As damage occurs on the local, European and global scale, all these scales are considered in the analysis.

Based on exposure-response functions physical impacts (mortality, morbidity such as non-fatal cancer, heart failure, asthma, bronchitis and so on) are calculated. Finally the resulting welfare losses are transferred into monetary values based on the concepts of welfare economics.

The impact pathway approach provides a logical and transparent way of quantifying externalities.

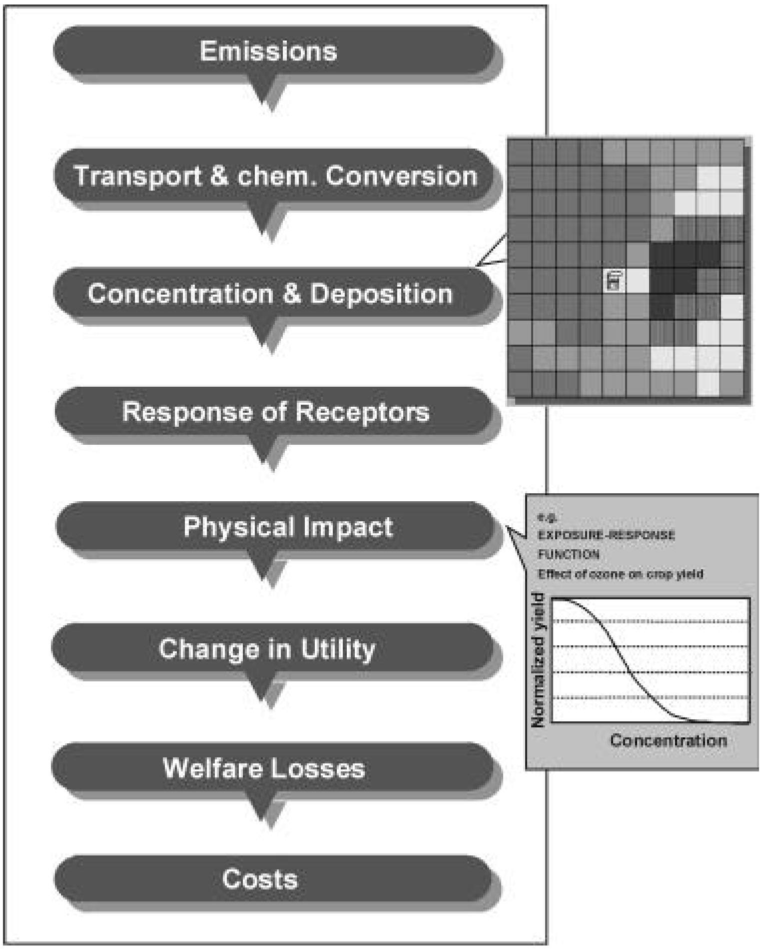


Figure 1: The Impact Pathway Approach

The method has already been extensively used to support decisions concerning a number of air quality directives of the European Commission (e.g. the draft ozone directive, the national emissions ceiling directive, the draft directive on non-hazardous waste incineration, air quality guidelines on CO and benzene), the UN/ECE multi-pollutant, multi-effect protocol and a number of national activities. The methodology is constantly further developed. In the current ExternE project ‘NewExt‘ a survey has beeen made to broaden the empirical basis for monetary valuation of risks reducing life expectancy due to air pollution. Furthermore, impact pathways for various pollutants in water and soil have been developed. In a number of other EC projects the methodology is extended to applications for industrial activities and for transport activities including a detailed analysis of noise impacts, accidents and congestion. Furthermore, the use of the method for green accounting is further developed.

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www.externe.info ExternE homepage with further information

# Workshop on Life Cycle Analysis and Recycling of Solar Modules

## ‚ The ExternE Methodology to Assess External Costs of Energy Conversion and Results for Electricity Generation‘

Rainer Friedrich

Motivation for estimating external costs

General methodology: the impact pathway approach

Exemplary results

ExternE IER

# External Costs Definition

**An external cost arises, when the social or economic activities of one group of persons have an impact on another group and when that impact is not fully accounted, or compensated for, by the first group.**

ExternE IER

## For what purpose are estimates of external costs needed?

Technology assessment: comparison of techniques, identification of weak points

Internalising external costs – ‚getting the prices right'

Cost-Benefit-Analyses, e. g. for measures and directives to protect the environment and human health

Sustainability and welfare indicator; assessment of impacts/ damage categories; priority setting.

ExternE IER

## "History" of ExternE

*Project ExternE* = ***Extern**alities of **E**nergy* **launched in 1991, financed by DG Research within the Joule programme scope: airborne pollutants from power plants, development of the Impact Pathway Approach**

- **Follow-up projects until now**
- **improving and extending the methodology, incorporating new knowledge**
- **extending the field of applications: heat production, transport , industrial activities**

ExternE IER

## Features of Estimates of External Costs

Marginal or ‚quasimarginal‘costs

Dependent on technology

Space and time dependent

Assessment of local, regional, European and global impacts

➢Bottom-up approach needed: the ‘impact pathway approach’

➢For comparison of technologies life cycle impacts have to be taken into account

ExternE IER

## Features of Estimates of External Costs

➢For assessment (weighting, comparison) of risks and damage of different damage categories the preference structure of the population is measured

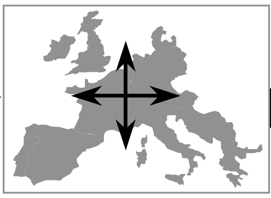
e.g. contingent valuation

ExternE IER

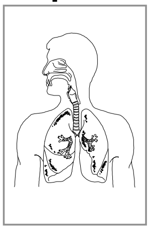
# Impact Pathway Approach

**Pollutant/Noise Emission**


**Transport and Chemical Transformation; Noise Propagation**



**Physical Impacts**

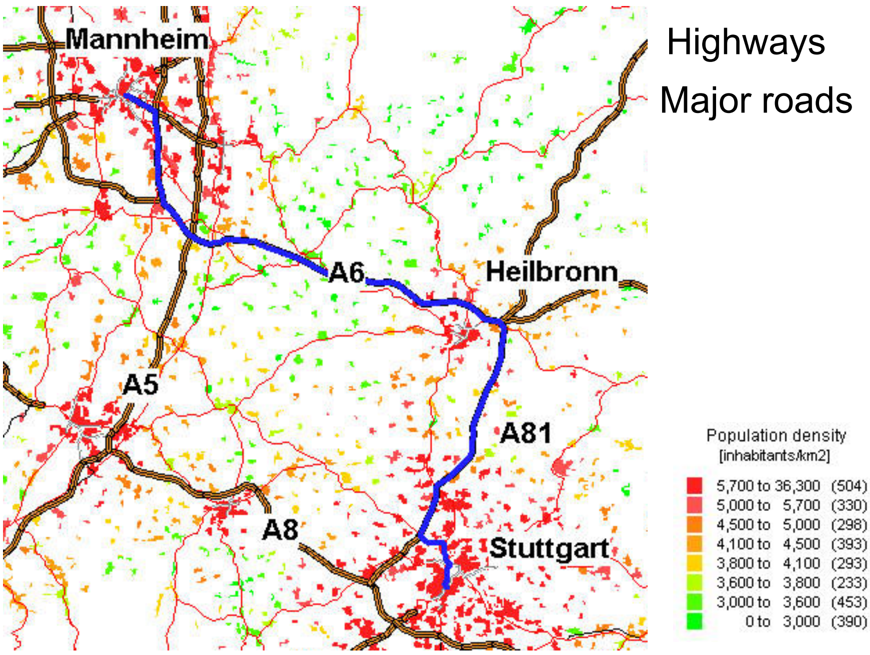


**Monetary Valuation**

ExternE IER

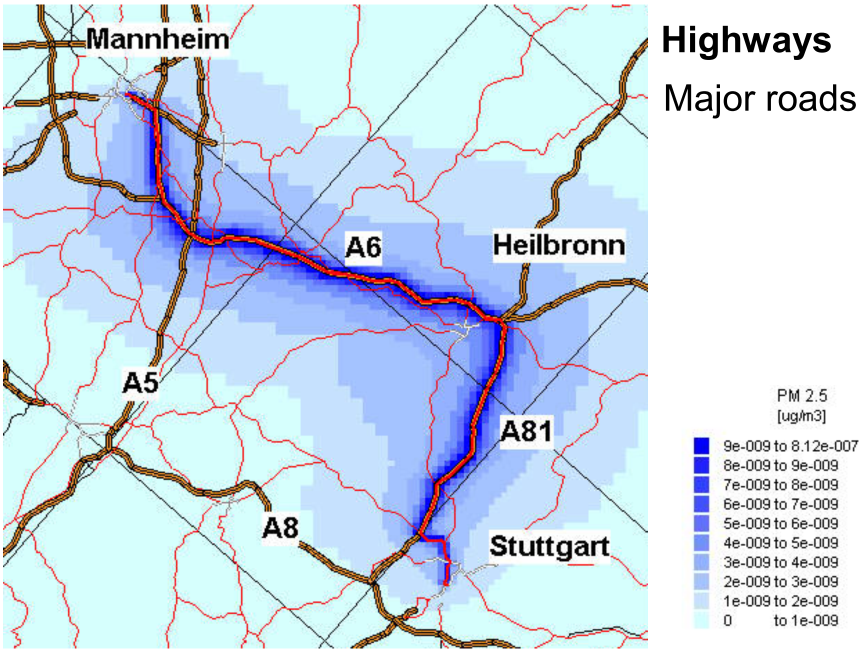
# Case-study: Stuttgart-Mannheim

## Trajectory and population distribution



ExternE IER

# Changes of $PM_{2.5}$ concentrations along highway due to diesel passenger car




ExternE IER

# Quantification of impacts and costs

Concentration Response Function:

Number of *Respiratory Hospital Admissions (RHA)*

$$= 3.46 \cdot 10^{-6} \cdot \Delta PM_{2.5} \cdot Population$$

Number of RHA due to 1 trip from Stuttgart to Mannheim by Diesel Passenger Car: **7.0 * 10$^{-8}$**

## Impacts included (I)

| Impact Category | Pollutant / Burden | Effects |
|---|---|---|
| Human Health – mortality | $PM_{10}$ | Reduction in life expectancy due to short and long time exposure |
| | $SO_2$, $O_3$ | Reduction in life expectancy due to short time exposure |
| | Benzene, BaP, 1,3-butad., Diesel part. | Reduction in life expectancy due to long time exposure |
| | Noise | Reduction in life expectancy due to long time exposure |
| | Accident risk | Fatality risk from traffic and workplace accidents |
| Human Health – morbidity | $PM_{10}$, $O_3$, $SO_2$ | Respiratory hospital admissions |
| | $PM_{10}$, $O_3$ | Restricted activity days |
| | $PM_{10}$, CO | Congestive heart failure |
| | Benzene, BaP, 1,3-butad., Diesel part. | Cancer risk (non-fatal) |
| | $PM_{10}$ | Cerebrovascular hospital admissions, cases of chronic bronchitis, cases of chronic cough in children, cough in asthmatics, lower respiratory symptoms |
| | $O_3$ | Asthma attacks, symptom days |
| | Noise | Myocardial infarction, angina pectoris, hypertension, sleep disturbance |
| | Accident risk | Risk of injuries from traffic and workplace accidents |

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## Impacts included (II)

| Impact Category | Pollutant / Burden | Effects |
|---|---|---|
| Building Material | $SO_2$, Acid deposition | Ageing of galvanised steel, limestone, mortar, sand-stone, paint, rendering, and zinc for utilitarian buildings |
| | Combustion particles | Soiling of buildings |
| Crops | $SO_2$ | Yield change for wheat, barley, rye, oats, potato, sugar beet |
| | $O_3$ | Yield change for wheat, barley, rye, oats, potato, rice, tobacco, sunflower seed |
| | Acid deposition | Increased need for liming |
| | N, S | Fertilising effects |
| Global Warming | $CO_2$, $CH_4$, $N_2O$, N, S | World-wide effects on mortality, morbidity, coastal impacts, agriculture, energy demand, and economic impacts due to temperature change and sea level rise |
| Amenity losses | Noise | Amenity losses due to noise exposure |
| Ecosystems | Acid deposition, nitrogen deposition | Acidity and eutrophication (avoidance costs for reducing areas where critical loads are exceeded) |

## Methods for monetisation

- **Market prices**

**only for goods traded on markets (e.g. crops, timber)**

**For non-market goods (public goods, human health risks):**

- **Indirect evaluation methods**

  **Hedonic pricing (wage differences due to risks, price changes of houses or rents due to difference in air pollution or noise)**

  **Travel costs, prevention costs**

- **Direct evaluation methods**

  **Contingent valuation, contingent ranking**



## Quantification of impacts and costs

Exposure Response Function:

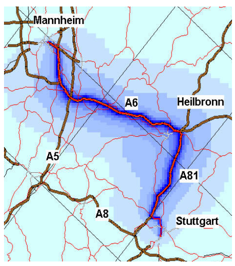
Number of *Respiratory Hospital Admissions (RHA)*

$$= 3.46 \cdot 10^{-6} \cdot \Delta PM_{2.5} \cdot Population$$

Number of RHA due to 1 trip Stuttgart-Mannheim by Diesel Passenger Car: **7.0 * 10^-8**

Monetary value: **4 320 €** per Hosp. Admission

Damage costs RHA per trip: **0.03 €-Cent**



## Monetary Valuation

### Average for West European Countries (best estimate)

| Health effects | Monetary value (€ $_{2000}$) |
|---|---|
| Value of a prevented fatality (VPF) | 1,040,000 |
| Year of life lost (chronic effects, 3% discount rate) | 50,000 |
| Cerebrovascular hospital admission | 16,730 |
| Respiratory hospital admission | 4,320 |
| Congestive heart failure | 3,260 |
| Chronic cough in children | 240 |
| Restricted activity day | 110 |
| Asthma attack | 75 |
| Cough | 45 |
| Minor restricted activity day | 45 |
| Symptom day | 45 |
| Bronchodilator usage | 40 |
| Lower respiratory symptom | 8 |

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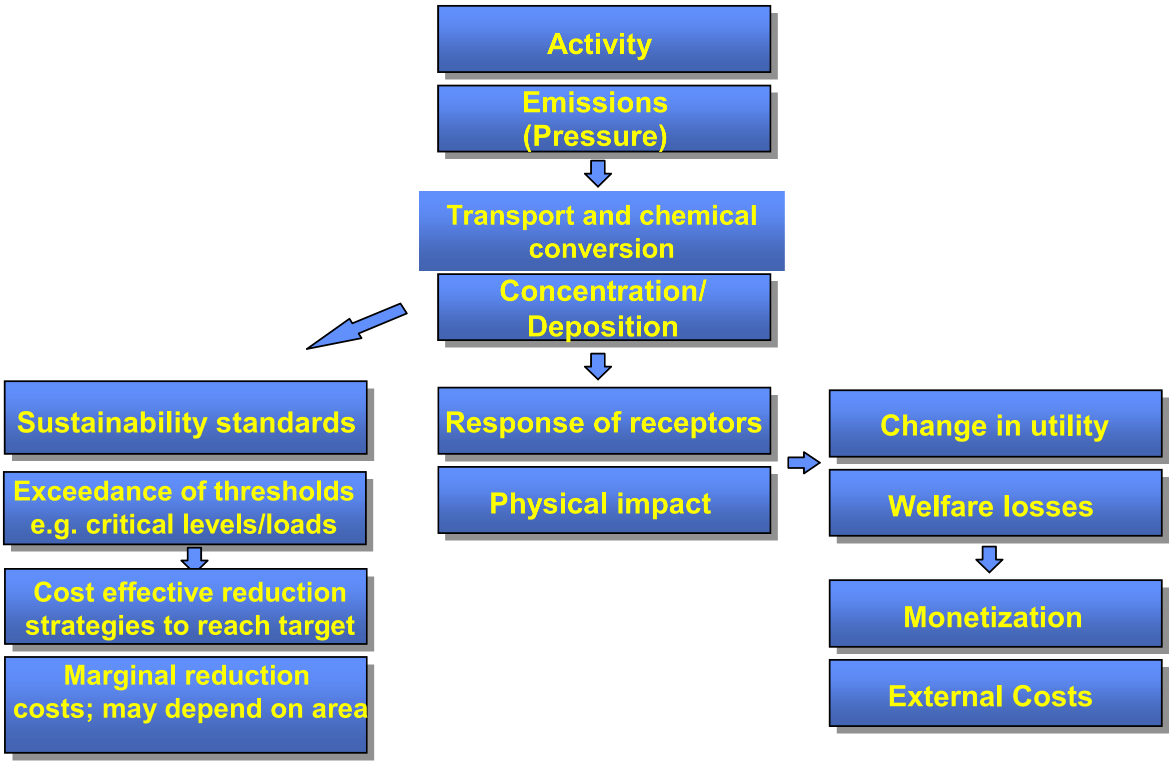
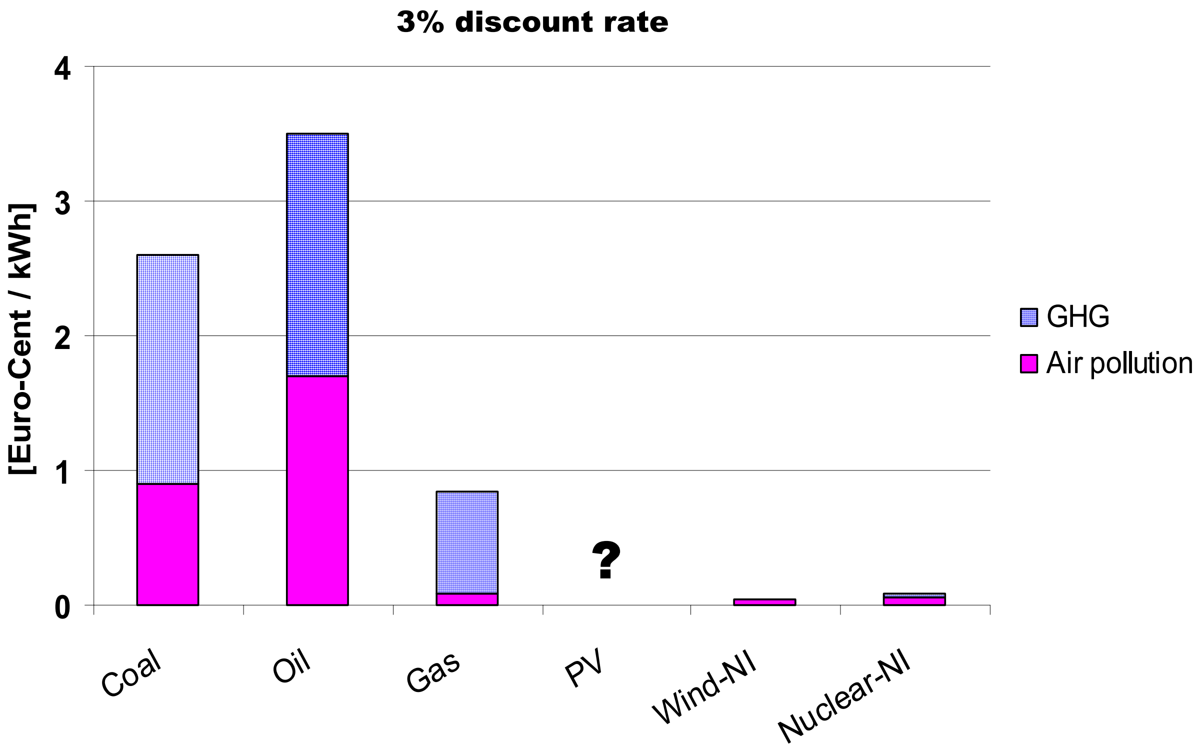
## Extended Impact Pathway Approach

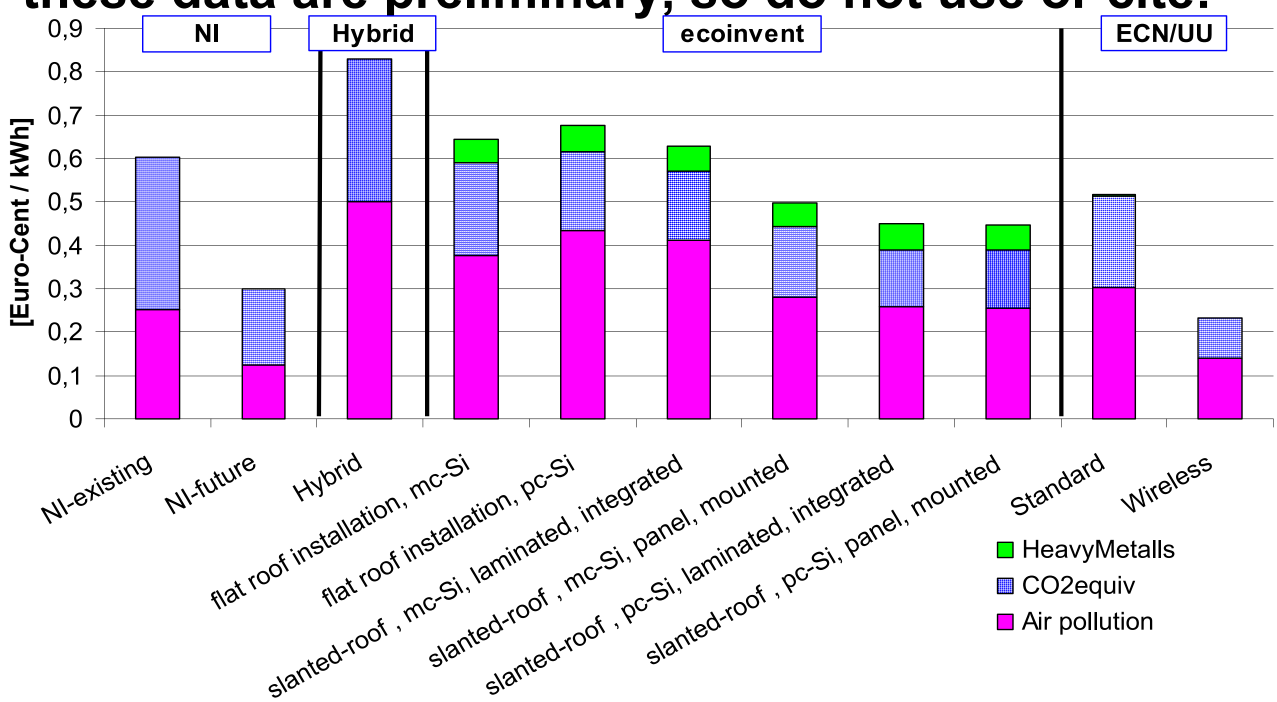


# External Costs of Electricity Production




# Preliminary External Costs PV in W-Europe

**these data are preliminary, so do not use or cite!**



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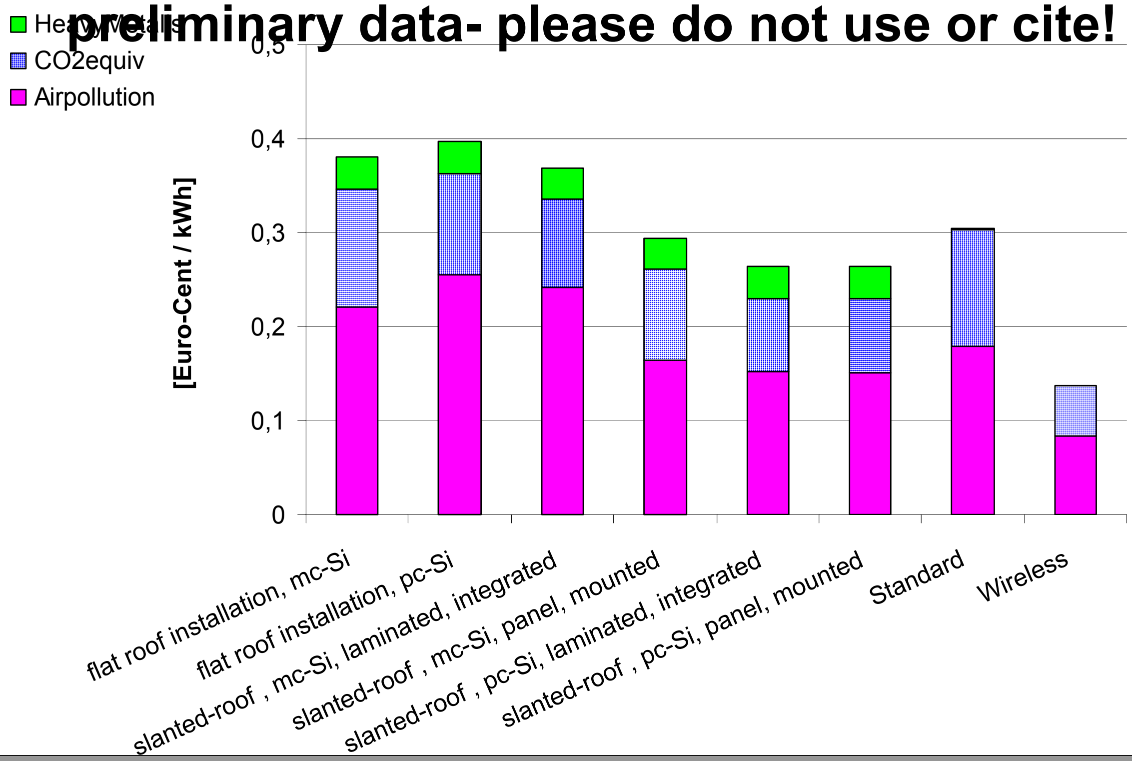
## Preliminary External Costs PV - Southern Europe

**preliminary data- please do not use or cite!**

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## Summary

- The *Impact Pathway Approach* is the state-of-the-art methodology for quantifying environmental external costs from energy conversion.
- External Costs vary with technology and site; for decision making the methodology should be used with appropriate input data, not simply some exemplary results.
- The methodology is being continuously improved and extended. Thus, according to the version of the methodology used different results will occur.

# Summary

- LCA data of high quality is needed to assess the external costs, especially for the assessment of renewable energy.
- External costs from PV mainly are caused during the production phase. External costs are not proportional to the energy consumption during the life cycle (CO2-emissions are fuel dependent, PM, NO, SO2 dependent on technology of energy conversion and fuel)!
- The external costs of air pollution are even more important than greenhouse gas emissions.
- Reducing the specific internal costs will reduce external costs.

# Recycling of Photovoltaic Modules

Karsten Wambach

Deutsche Solar AG, Germany

PV modules today are known as very stable and reliable products. The average lifetime is estimated to be more than 25 years. Despite this an increasing number of end-of-life modules and rejects from production can be observed all around the world. At present defect modules can be disposed at special landfill sites at rather low costs without problems since they are very resistant to environmental attack. This is frequently not acceptable for end users who demand the reuse and recycling of the defect PV products. Several companies and research institutes worldwide have been working on technologies for recycling crystalline silicon solar cells and thin film modules though the amount of waste is at least 3 orders of magnitude less compared to other electronic equipment. In principle solar modules are electronic and electric equipment but are not yet integrated in the European waste electrical and electronic equipment (WEEE) directive. The German environmental agency has finished a study recently to integrate PV modules in a new revision of the directive. This will have serious consequences for the European photovoltaic industry. Based on the “POLLUTER PAYS”- principle the PV industry is obliged to pay for the future waste treatment of their products causing long term liabilities. Most of the end of use modules are considered to be industrial waste that will be monitored and have to be recycled. Even restrictions in PV waste transportation and storage might occur. The restriction of the use of certain hazardous substances in electrical and electronic equipment (ROHS) can limit the use of solder alloys, copper tabs, screen printing pastes or compound semiconductors in PV modules in the future and can even cause a classification as hazardous waste for some products.

First recycling solutions are in a pilot plant state at present. Deutsche Solar AG put the first thermal recycling line dedicated to PV modules of any technology and manufacturers in operation recently. With respect to increasing waste amounts from production, transportation or installation and from field installations of PV generators the capacity of the pilot plant is sufficient to recycle the collectable end-of-life modules in Europe at present. Running several lines today will therefore not be cost effective. The recycling process of First Solar’s pilot plant in USA is dedicated to CdTe modules of their own production.

For this reason Deutsche Solar’s pilot line is run as an open activity to everybody. With the further growing market the technology can be copied and decentralized. Within this paper a survey on frequently module failures, experiences from the collection of the products and recycling results are presented. Within present and forthcoming European and German legislation possible types of recycling strategies, expected costs and the consequences for new products are discussed. The solution of Deutsche Solar AG is presented.

The recycling process is carried out in 2 steps.

At first the modules are placed in a special furnace after removal of cables, frames or junction boxes to burn off the non-recyclable polymers under well controlled conditions at about 500°C. The inorganic materials of the modules like glass, copper, aluminium etc. are collected separately, to be reused in high value established processes. Thanks to the well controlled process the solar cells can be recovered in high yields without damage of the wafers.

In a second process step the solar cells collected are etched back to the bare silicon by removing metallisation, antireflective coating and diffusion layers. The wafers can be used for new solar cell production exactly like new wafers, without any loss of efficiency at competitive costs. Broken wafers can be used as feedstock for new wafer production.

The costs of waste treatment are generally included in the costs of all components in the value chain but not yet for modules at the end of their life. These module waste costs can be calculated between 0.10 €/Wp and 0.40 €/Wp depending on type of module, transportation waste treatment and disposal costs. Modules with crystalline silicon solar cells benefit from successful recovery of wafers to cover at least parts of the end of life costs but thin film modules may suffer from the low value of the separated products. The energy consumption using a reclaimed wafer is about 20 – 30% compared to a new wafer in a module thanks to avoidance of new crystallisation and cutting.

## Recycling Of Solar Modules

Dr. Karsten Wambach
Deutsche Solar AG
Solar Materials



## European Waste Policy
## Principles and Ranking

- **Polluter pays**

| | |
|---|---|
| • Avoid | durable products |
| • Reuse | repair |
| • Recycle | disassemble |
| • Dispose | minimize waste |

## Waste Classification (subject to change)

- Codes

16 not specified

| | |
|---|---|
| 160214 | electronic waste |
| 160213* | hazardous electronic waste |

17 construction, demolition waste

| | |
|---|---|
| 170202 | glass |
| 170204* | contaminated glass |

20 municipal waste

| | |
|---|---|
| 200102 | glass |
| 200135* | hazardous electronic waste |
| 200136 | electronic equipment |
| 200399 | other not specified |

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## What Happened?

- PV modules included in article 13 of WEEE (by UBA)
- Ökopol finished study
- UBA report to BMU ready
  - End of life modules considered as industrial electronic waste in most cases
- Draft of „Gesetz über Elektro- und Elektronikgeräte“ (ElektroG)

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## What will happen?

- UBA will publish study in April (www.umweltbundesamt.de)
- Ministry will have to decide on
  - Classification of products
  - Inclusion in WEEE or
  - Inclusion in national acts and ordinances
  - Recycling quotas
  - Long term waste treatment financing (25 – 30 years)

Inclusion of PV modules not expected in 2004

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## Present Situation

- Modules - electronic power components
- Durable design but not necessarily easy recycling
- Contain heavy metals, e.g. Pb, Sn, Ag etc. (1%)
- Contain non recyclable parts (Tedlar, EVA, inorganic fillers)

- High demands on the decomposition company
- Insufficient declaration of the used materials
- Quota of recycling > 80 % possible
- Manufacturer will take a financial share on the collecting system

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# Economics

- Non hazardous waste transportation €200/t
- Trash non regulated landfill €100/t
- Costs 4 – 10 Cent/Wp
- 30 - 40 Cent/Wp as hazardous waste



# PV-Recycling

- Pro-active, long term environmental strategy
  - prevent environmental damage by its processes and products
  - includes recycling manufacturing waste and spent PV modules
  - year 2020 higher waste forecast
  - today's material selection and module design - a precedent for the future

## End of Life Modules, Typical Damages

- **Broken glass**
  - spontaneous breakage
  - transport- and assembly defect
  - storm
  - lightnings
- Defect laminate
  - delamination
  - yellowing
  - low backsheet adhesion
- **Electrical defects**
  - broken connector
  - isolation
  - bypass diode
  - hot spot
  - cable- or plug corrosion
- Further losses
  - design mistakes
  - process losses

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## Task Force Activities

- Municipal vs. Industrial waste
- Classification of module wastes (European Waste Codes)
- Collection systems, voluntary PV take back system
- Transportation and storage
- Decomposition/ disposal
- Financing systems, escrow funds, 25 –30 years future liabilities
- Exemptions from ROHS
- Cooperation with european and national agencies and associations
- Recommendations and guidelines
- Legal issues

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## Cooperations

- Support of Associations
  - EPIA
  - BSi
  - UVS
- European Commission
- Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU)
- Lawyers

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## PV-Recycling at Deutsche Solar

- Module recycling (pilot plant)
  - Multicryst. silicon cells
  - Monocryst. silicon cells
  - Thin film modules (research)
- Solar cells
  - Rework of out of spec. cells
  - Surface treatment
- Wafer recycling
  - Wafer washing
  - Surface treatment

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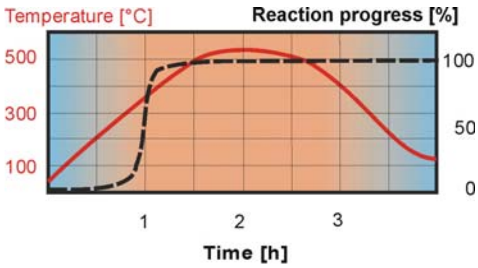
# Pilot Facility

Furnace and waste gas treatment facility in operation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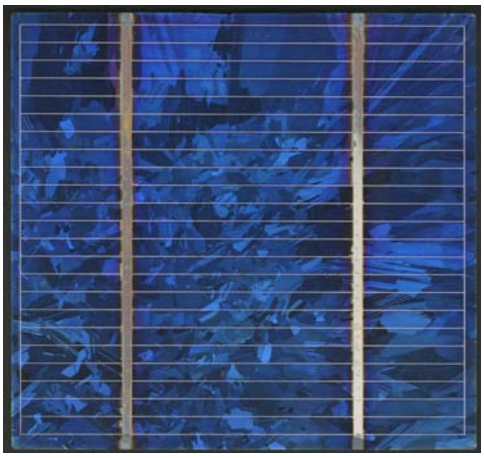
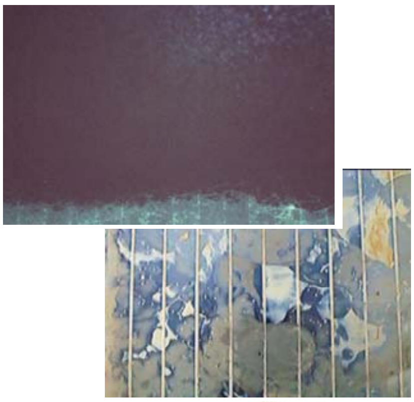
# Recovered Wafer and a-Si Module





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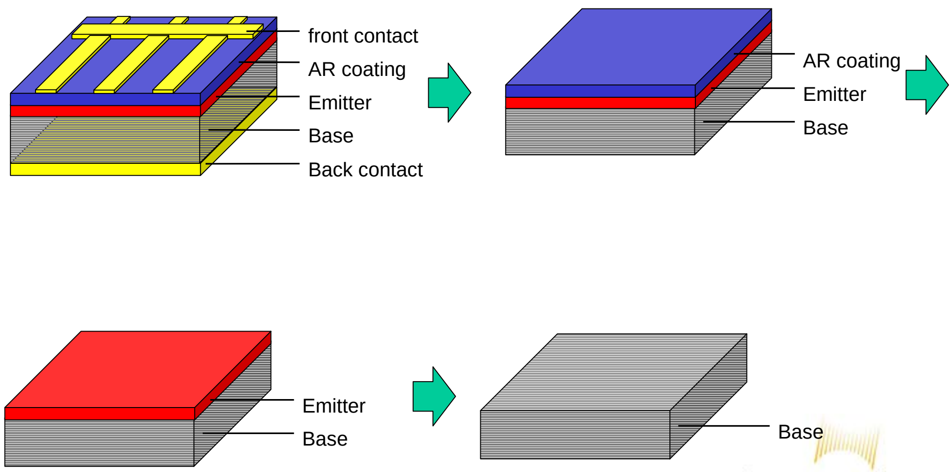
# Recycling of Solar Cells

- Recycling of cells from process failures
- Recycling of solar cells from modules
- Wafer surface properties  can be widely adjusted



# Recycling of Solar Cells



## Recycled Wafer

**Prior positions of busbars and grid may be visible**

**Screen printing in same position at same efficiency possible**

**advantage:**

**cost reduction**

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## Advantages of Solar Cell and Module Recycling

- completion of environmentally friendly cradle to grave strategy of PV of excellent public acceptance
- cost effective solution of waste treatment questions
- offering high quality wafers at moderate costs
- saving of about 80% of energy in a module compared to the use of new silicon wafers
- multi-recycling of crystalline silicon possible
- increase in PV energy harvest

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# Compound semiconductor solar cell recycling
# -
# Understanding recycling as a part of the complete life cycle chain -

N. Warburg, M. Shibasaki*, J. Springer**, K. Wörsing***, M. Irasari****

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** Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg, Germany
*** Fraunhofer-Gesellschaft, Institut für Chemische Technologie, Pfinztal, Germany
**** GAIKER Technology Center, Zamudio, Spain

Closing the loop in the life cycle of products, preserving natural resources, reducing environmental impacts and simply saving money are the main drivers for the development and application of recycling systems. This counts especially for solar cells, as this approach of electricity generation aims to contribute significantly to a sustainable future.

However, it has to be clearly understood and considered that recycling is not per se environmental friendly and advantageous, even if a lot of people seem to think it is. Environmental impacts as well as costs of a recycling system should not exceed the “primary production” from virgin materials. Only if the recovery of materials uses less energy and causes less emissions compared to the virgin production, this will lead to an overall reduction of environmental impacts and energy consumption and therefore for example also reduce numbers like energy payback time. The environmental and economic „break-even“ can serve as a decision support, e.g. to figure out whether a recycling process is efficient enough or at which depth a recycling process should be aborted.

As a consequence, a substantial requirement for the development of a recycling concept is the calculation of environmental impacts and costs for the production, use and recycling of the respective product. The information concerning environmental impacts of the use phase seems to be irrelevant in this context, but in the end it is not since decisions for changes in production (e.g. usage of a better recyclable material) can have significant influence on the use phase (e.g. by a changed efficiency factor as a consequence of the new material). A so called “shifting of burdens”, an improvement of one life cycle phase while worsening another, can be avoided by applying a holistic approach like LCE (see below).

In the project SENSE, funded by the EU in the 5th framework programme, the approach of Life Cycle Engineering (LCE) is used to analyse thin-film solar cells, to support the development of recycling processes and to optimize solar cells (Figure 1).

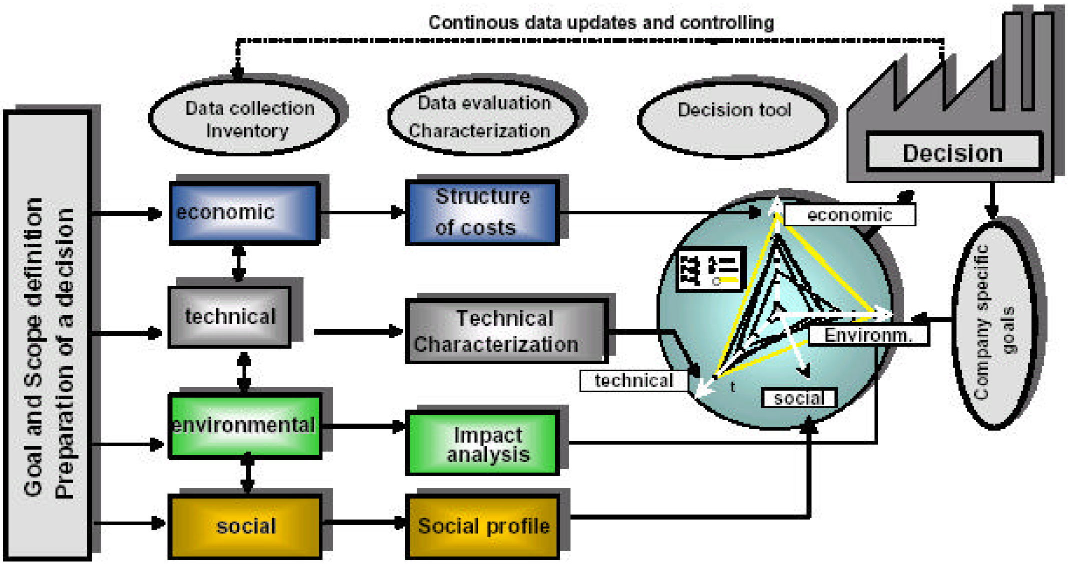


Figure 1: LCE as decision support tool

Development of ecycling in SENSE The approach of thin-film cell recycling in SENSE follows the insights described above. The ongoing development started with preliminary test as presented in Figure 2. Thin film solar cells have been treated with various recycling equipment available in the machine park of the partners.

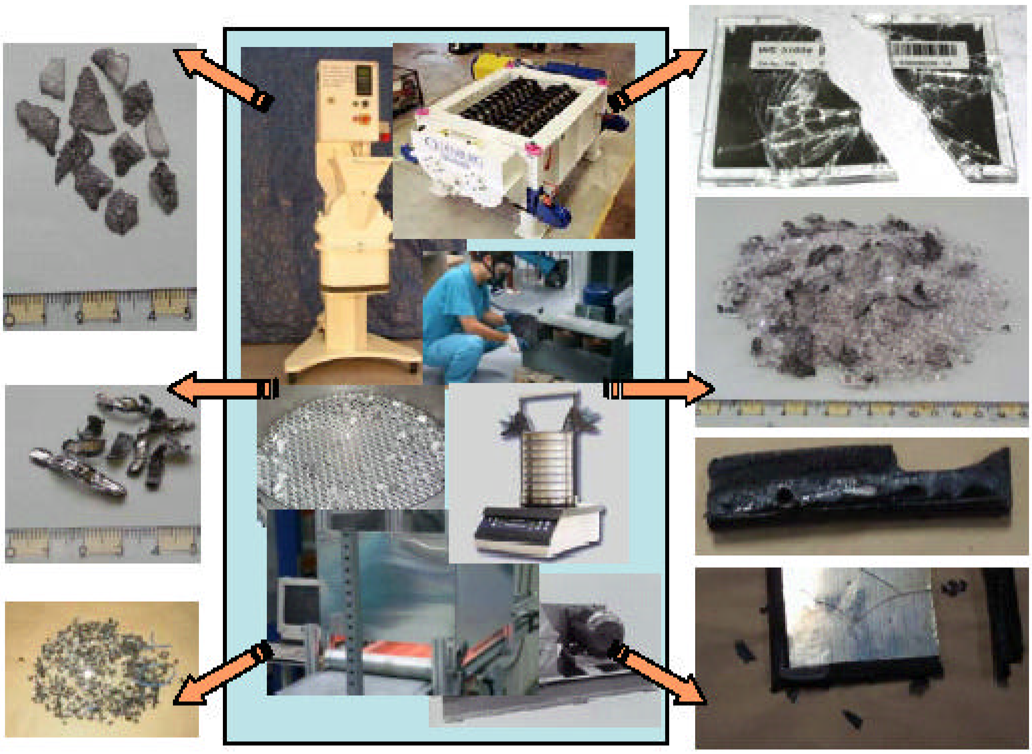

Figure 2: Recycling of thin-film cells, screening test

In Figure 3 a first overview of the recycling options for the product “thin-film solar cell” is presented.

| | CIS | a-Si | CdTe |
|---|---|---|---|
| **Dismantling** | | X | |
| **Crushing & Grinding** | | | |
| separation by grinding | | | |
| Analysis of valuable materials in fractions | | X | |
| elimination/ reduction of dust /safety at work issues | | | |
| Analysis of machine wear. Evaluation of grinding equipment | | | |
| **Thermal treatment** | | | |
| Heating graphics (to avoid crackling) | | X | ? |
| Oxidation of valuable materials | | X | |
| **Hot wire cutting** | | | |
| Laboratory system for small panels or panel cuts | | X | ? |
| Pilot system for big panels | | X | ? |
| **Ablation, Sandblasting** | | | |
| Sandblasting in big panel surfaces (cracked, and not cracked) | | X | |
| Sandblasting glass grist, abrasion in mixing reactor | ? | ? | ? |
| Separation of sand and valuable materials | | ? | |
| **Water jet cutting** | | | |
| Adaptation of cutting system to horizontal aplication | $ | X | $ |
| Separation of EVA and valuable materials | | X | |
| Separation of water and valuable materials | | X | |
| **Chemical treatment** | | | |
| Organic dilution of EVA | | X | |
| efluent management/ environmental/ safety issues | | | |
| Development a multi-stage material winning process | | X | |
| efluent management/ environmental/ safety issues | | | |
| **Glass melting** | | | |
| Exploration of the possibility of adding to recycled glass grist | | | |

GAIKER

ICT

BOTH

X unlikely

$ expensive system

Figure 3: Recycling technologies – Screening on availability, price, technology

The knowledge of various recycling technologies and economic and environmental targets (“ecologic and economic target-costing”) will lead to an optimal recycling solution and optimized solar cell life cycle. This contributes to the further development of a sustainable energy supply for Europe.

# Compound semiconductor solar cell recycling

- Understanding recycling as a part of the complete life cycle chain -

**N. Warburg, M. Shibasaki*, J. Springer**, K. Wörsing***, M. Irasari******

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** Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg, Germany
*** Fraunhofer-Gesellschaft, Institut für Chemische Technologie, Pfinztal, Germany
**** GAIKER Technology Center, Zamudio, Spain

Contact: warburg@ikp2.uni-stuttgart.de



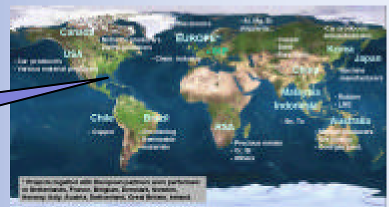
## Contents

- Introduction to IKP and SENSE
- Why recycling?
- LCA, LCE, DfE
- Development of solar recycling processes

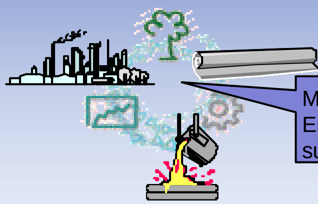
IKP Universität Stuttgart GaBi
Institut für Kunststoffprüfung und Kunststoffkunde
Brussels 18March2004.ppt

## Introduction IKP -I-
IKP, dept. Life Cycle Engineering (LCE) at University of Stuttgart

- Dept. LCE founded in 1989 by Prof. Dr.-Ing. Peter Eyerer
- Interdisciplinary team of 10 full time academic staff (Chemical, mechanical, environmental and process engineers; geoecologist)



Industry and research projects on ecological-economic-technical analysis and decision-support of products, processes and services



Methodology development (Life Cycle Engineering and Sustainability, substance flow analysis, Indicators)


Software and database development and maintenance (GaBi software, DfE-tools)



## Introduction IKP -II-
Working fields

- **Automotive industry** e.g. DaimlerChrysler, Porsche, Renault, Delphi,...
- **Material industry** e.g. Alcan, Borax, Falconbridge, Amplats, ThyssenKrupp ...
- **Construction industry** e.g. Maxit, Heidelberger, Saint Gobain, STO,…
- **Electronics industry** e.g. Motorola, Nokia, Bosch, LG Electronics, Sony, …
- **Chemical industry** e.g. DOW Chemicals, BASF, DSM, PPG, Dmc$^2$, …
- **Surface technology** e.g. BASF, PPG, Dürr, DuPont…
- **Renewable resources** as energy carriers, for automotive applications etc.
- **Energy Supply** e.g. NWS, NIRE/MITI, NorskHydro, Icelandic NewEnergy, ...
- **End of Life / Recycling** e.g. DGfH, ECVM, Siemens, Noell, Thermoselect, …

- Development and distribution of **GaBi Software-System and databases** together with development partner PE Europe GmbH

Together with our partner, PE Europe, we are forming the world‘s largest LCA working group

## SENSE
funded in the 5th framework programme

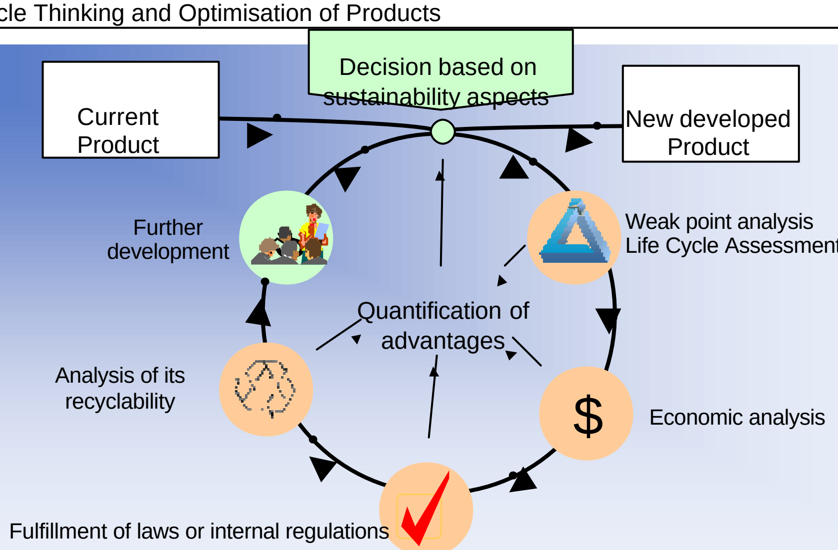
SENSE
Sustainability EvaluatioN of Solar Energy systems

Partners (alphabetic): Ambiente Italia, Free Energy Europe, GAIKER, ICT, IKP, Umicore, Würth Solar, ZSW

- LCE of solar cell life cycle including the new recycling processes (optimisation, potentials, weak points)
- Development of recycling strategies for thin-film solar cells
  - ➢ Recycling has to make SENSE
    - technically
    - economic
    - environmentally



## (Re-)developing products
Life Cycle Thinking and Optimisation of Products



- Introduction IKP and SENSE

- Why recycling?

- LCA, LCE, DfE

- Development of solar recycling processes





**Recycling is carried out to**

- earn money
- save resources
- reduce environmental impacts
- reduce waste

**Statements**

- ➢ Recycling is not per se environmental friendly
- ➢ Mass-based recycling quotas (e.g. WEEE) are a first step in the right direction, but having questionable environmental effects
- ➢ Effect-oriented approaches should be preferred (EuP)

- Introduction IKP and SENSE

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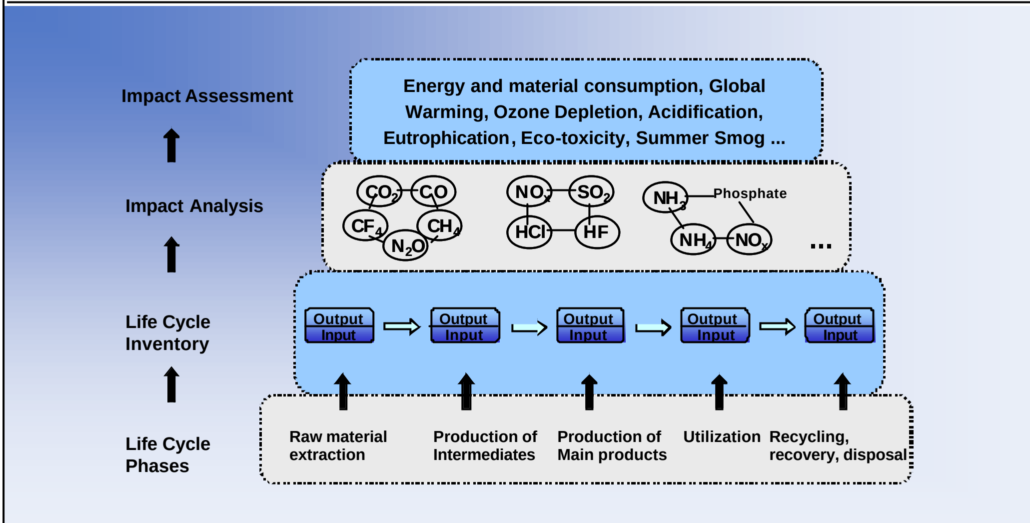
## Methodological approach
based on LCE/DfE

*To reach the challenging goals the following aspects are tracked* <u>*design accompanying*</u>
- technical feasibility
- environmental aspects
- cost aspects

*Necessary know-how and data are delivered by*
- experienced recyclers
- LCA experts
- close cooperation of producers and recyclers

*Statements*
➢ recycling technology exists and can be adapted to solar cells recycling
➢ LCA (and LCE) has developed to a reliable and applicable methodology

## LCA
Life Cycle Assessment

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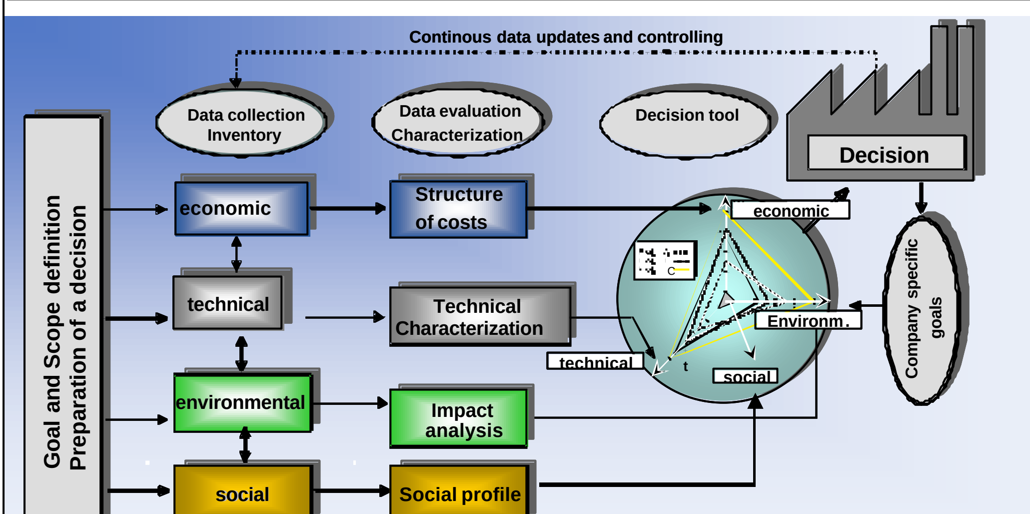
## LCE
Sustainability, decision support

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## From LCA to DfE

### Life Cycle Assessment (LCA)

Life Cycle Assessment is calculating the potential environmental impact caused by the production, use and End of Life of a product.

### Life Cycle Engineering (LCE)

LCE studies analyze the economic, environmental and technical aspects and potentials through life cycles of products, systems and services.

### Design for Environment (DfE)

Design for Environment uses life cycle thinking and evaluated environmental data from LCA in combination with technical and economic information to perform decision support for new designs.



## LCA in the design process

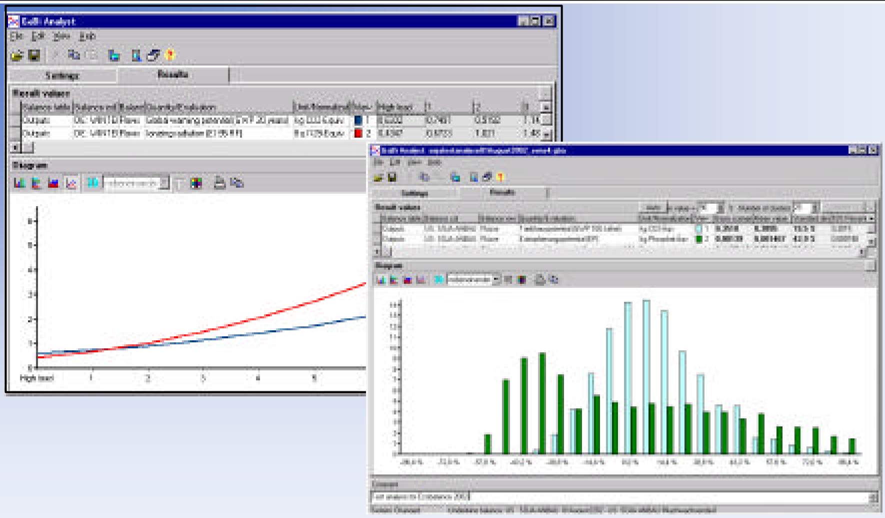
State of the art - differences to DfE

***Overall goal: Support of the development of environmental friendly products***

| | Life Cycle Assessment (LCA) | Design for Environment (DfE) |
|---|---|---|
| **Goal:** | **- environmental analysis of defined systems** | **- improvement of products<br>- engineering tool for operative decisions** |
| **Method:** | **- scientific background<br>- system analysis on basis of process chains** | **- multi criteria method** |
| **Audience:** | **- experts, environmental Manager, research engineers, authorities** | **- designers, architects** |
| **Results:** | **- discussion of results (round table)<br>- weak point analysis** | **- actions and new designs** |

**LCA as basis for DfE**

## Taking the chance to do a “real” DfE
based on on LCE know how and highly flexible software systems





- Introduction IKP and SENSE
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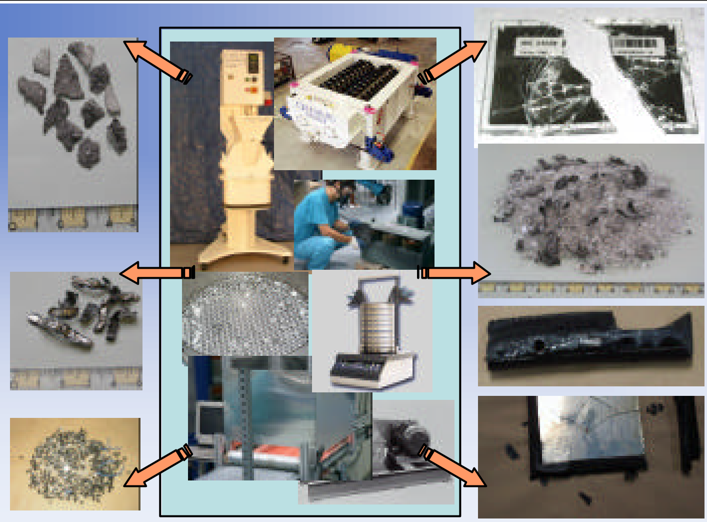
## Recycling of thin-film solar cells
first tests



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## Recycling of thin-film solar cells
technology matrix

| | CIS | a-Si | CdTe |
|---|---|---|---|
| **Dismantling** | | X | |
| **Crushing & Grinding** | | | |
| separation by grinding | | | |
| Analysis of valuable materials in fractions | | X | |
| elimination/ reduction of dust /safety at work issues | | | |
| Analysis of machine wear. Evaluation of grinding equipment | | | |
| **Thermal treatment** | | | |
| Heating graphics (to avoid crackling) | | X | ? |
| Oxidation of valuable materials | | X | |
| **Hot wire cutting** | | | |
| Laboratory system for small panels or panel cuts | | X | ? |
| Pilot system for big panels | | X | ? |
| **Ablation, Sandblasting** | | | |
| Sandblasting in big panel surfaces (cracked, and not cracked) | | X | |
| Sandblasting glass grist, abrasion in mixing reactor | ? | ? | ? |
| Separation of sand and valuable materials | | ? | |
| **Water jet cutting** | | | |
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ICT

BOTH

X unlikely
$ expensive system

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## Summary

In SENSE, beneath other issues,

- recycling processes for a-Si, CdTe and CIS solar cells are developed by experienced recyclers

- development is supported by applying LCA results and know

- development is supported by producers and material suppliers

to ensure a senseful recycling in terms of environmental and cost aspects



Thank you for your attention

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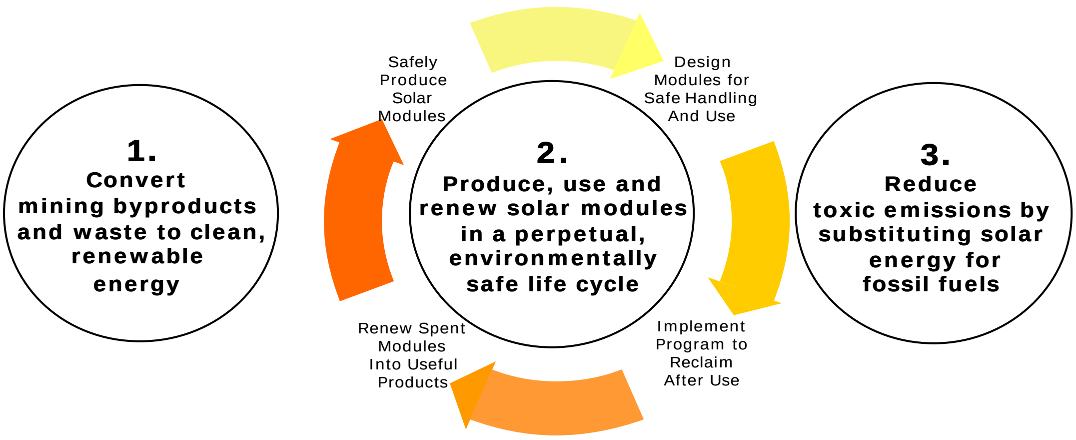
# Recycling of Compound Semiconductor Modules

Rainer Gegenwart

First Solar

First Solar is producing high performance PV modules based upon the CdTe technology. The first production plant went into operation in 2002 and a plant expansion program is under way that will expand the total manufacturing capacity to 25 MW by 2005. The First Solar PV modules are not only designed for optimum performance but also for recycling after reaching the end of their life. The life cycle of our solar products is designed as a closed loop.

First Solar is committed to preserve the environment and has developed a three point plan to help preserve the environment.




The active semiconductor of First Solar´s PV modules, CdTe, has unique properties and the processes developed by First Solar makes this material ideal for cost efficient production. The Cd in the semiconductor is derived from mining byproducts.

The entire production line is designed as a zero emission factory and exceeds regulatory emission standards. End of life modules, production scrap, and modules broken during installation are reclaimed and recycled in First Solar´s production facility. The reclamation program is part of First Solar´s product warranty. The customer who is seeking to return solar modules is shipping the modules to First Solar´s reclamation site upon First Solar´s expenses.

The recycling pilot line at First Solar´s production site in Perrysburg, Ohio was commissioned in 1998. Spent modules and production scrap are crushed in a hammer mill. EVA encapsulant material is separated in a milling process. An etching process then separates the glass and metal fractions. After neutralization and dewatering the metals are pressed through filters and the filter cake is then shipped to a metallurgical company to separate and reuse the metals. Just cables and external components are removed before the process.

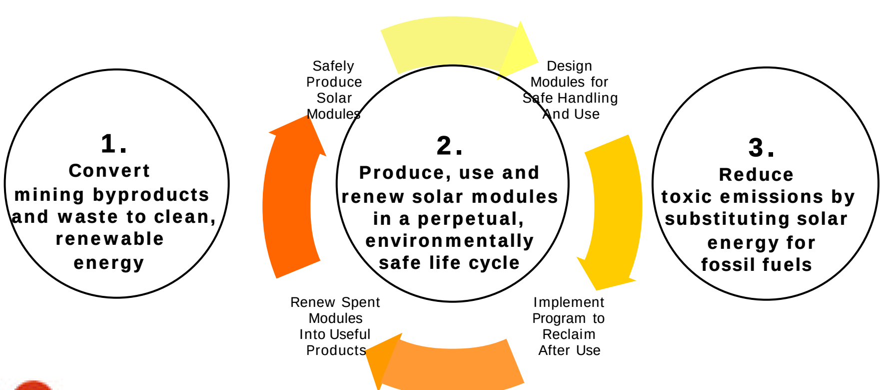
The capacity of First Solar´s recycling facility is up to 1400 kg per day. Annually up to 1.5 MWp of PV glass/glass laminates can be processed in this plant which by far exceeds current return rates and production scrap. First Solar is virtually recycling the entire module including all of the semiconductor materials.

# First Solar

Recycling of Compound Semiconductor Modules

Rainer Gegenwart
Brussels, March 18, 2004

# First Solar's Three Point Plan to Help Preserve the Environment



1\. Convert mining byproducts and waste to clean, renewable energy → 2. Produce, use and renew solar modules in a perpetual, environmentally safe life cycle → 3. Reduce toxic emissions by substituting solar electricity for fossil fuel generation

- The active semiconductor in First Solar modules, CdTe, has unique properties that make it ideal for producing low cost solar electricity.
- First Solar obtains 100% of the Cd and Te used in its modules from mining byproducts.
- By converting these industrial wastes into economical, high performance solar modules, First Solar not only removes a risk but creates a benefit to the environment.

First Solar.



1\. Convert mining byproducts and waste to clean, renewable energy → 2. Produce, use and renew solar modules in a perpetual, environmentally safe life cycle → 3. Reduce toxic emissions by substituting solar electricity for fossil fuel generation

**Safe production of solar modules**

- Manufacturing generates no external hazardous air emissions
- First Solar is completing ISO 14000 certification in 2004.
- Emissions from production process are below regulatory emissions standards.
- Recycling and treatment process reclaims and recycles virtually all manufacturing waste.
- Rigorous plant safety practices are recognized for their excellence by independent health and safety experts.

First Solar.

1\. Convert mining byproducts and waste to clean, renewable energy → **2. Produce, use and renew solar modules in a perpetual, environmentally safe life cycle** → 3. Reduce toxic emissions by substituting solar electricity for fossil fuel generation

## Program to Reclaim Modules After Use

- First Solar reclaims module scrap in the manufacturing production line.
- First Solar provides convenient, effective procedures for customers to return spent modules to First Solar for recycling.
- First Solar will prefund anticipated module return and recycling costs with annuity to be issued by a major international insurance company.

First Solar.



1. Convert mining byproducts and waste to clean, renewable energy → **2. Produce, use and renew solar modules in a perpetual, environmentally safe life cycle** → 3. Reduce toxic emissions by substituting solar electricity for fossil fuel generation

## Renew spent modules into useful products

- First Solar offers a comprehensive recycling program that extracts and re-uses virtually the entire module, including all of the semiconductor materials.
- Metals and other components are extracted from the modules through multiple processing steps and recycled, or held for recycling, into new products.

First Solar.

# First Solar

Recyling of Solar Modules

2.
Produce, use and renew solar modules in a perpetual, environmentally safe life cycle

## Program to Reclaim Modules After Use

First Solar provides convenient, effective procedures for customers to return spent modules for recycling.

- For every module it sells, First Solar proposes to fund an annuity to cover anticipated module return and recycling cost at the module´s end-of-life
- Annuity contracts are purchased annually to cover all modules sold during each calendar year.
- End-of-life assumptions are reviewed and annuities are reinvested periodically to assure full coverage of anticipated module return and recycling costs.

2.
Produce, use and renew solar modules in a perpetual, environmentally safe life cycle

## Program to Reclaim Modules After Use

First Solar provides convenient, effective procedures for customers to return spent modules to First Solar for recycling.

- For customers seeking to return or dispose of First Solar modules at any time and for any reason:
  - First Solar supplies shipping instructions and location.
  - First Solar pays all packaging and shipping costs.
  - The customer's only requirement is to ship, at First Solar expense, per instructions.
- First Solar commits to this reclamation program in its standard product warranty.
- First Solar tracks modules sold and returned by serial number so that it can account for the date of sale, customer and destination of each module, the anticipated return date (assuming a 20 year life), and the modules returned for recycling.

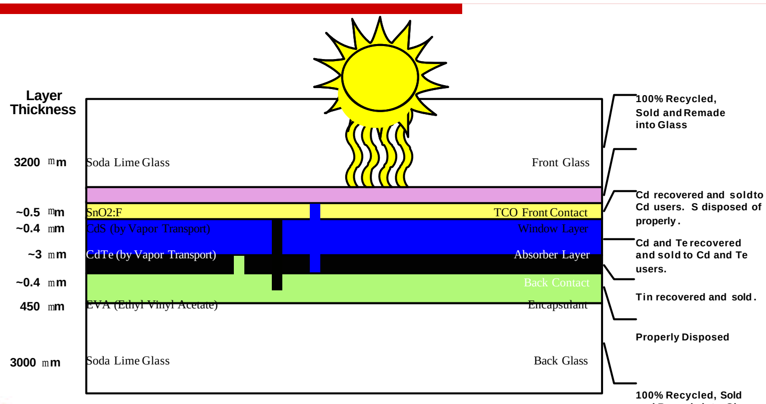
First Solar.



2.
Produce, use and renew solar modules in a perpetual, environmentally safe life cycle

## Renew Spent Modules into Useful Products

First Solar recycles virtually the entire module, including all of the semiconductor materials.




First Solar.

2.
Produce, use and renew solar modules in a perpetual, environmentally safe life cycle

## Renew Spent Modules into Useful Products

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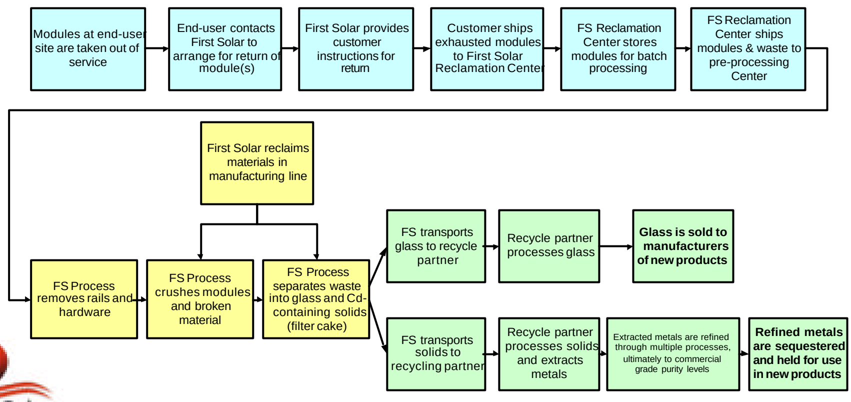



First Solar.

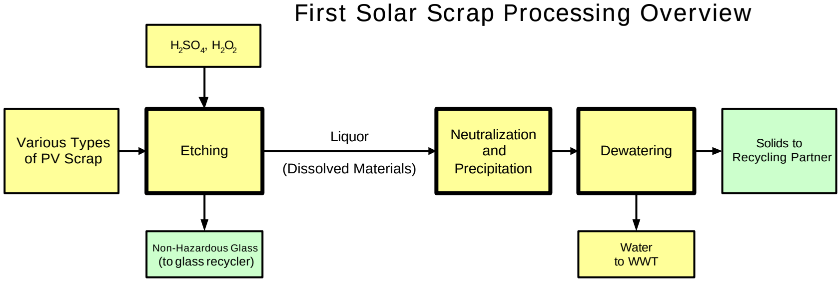


2.
Produce, use and renew solar modules in a perpetual, environmentally safe life cycle

## Renew Spent Modules into Useful Products

First Solar recycles virtually the entire module, including all of the semiconductor materials.

### First Solar Scrap Processing Overview



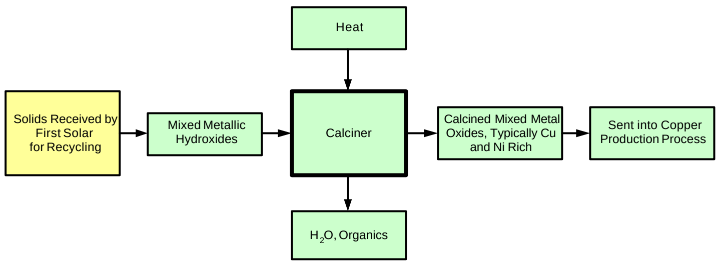

First Solar.

2.
Produce, use and renew solar modules in a perpetual, environmentally safe life cycle

## Renew Spent Modules into Useful Products

First Solar recycles virtually the entire module, including all of the semiconductor materials.

First Solar's Recycling Partner Process Overview




First Solar.



2.
Produce, use and renew solar modules in a perpetual, environmentally safe life cycle

## First Solar Recycling Facility

Waste forecast for First Solar´s production volume

- Waste stream from transportation, installation, and module breakage during the first year is estimated to be 3 % (Oekopol 2004)
- Production 2004: 100.000 modules, 1.140 t
- Production 2005: 333.000 modules, 3.800 t
- Waste stream 3 %: 34 t in 2004
  114 t in 2005

First Solar.

2.
Produce, use and renew solar modules in a perpetual, environmentally safe life cycle

## First Solar Recycling Facility

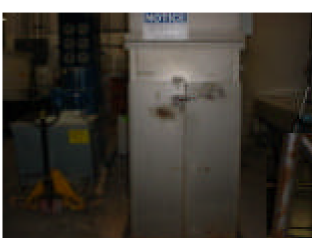
First Solar provides a technology to recycle broken modules, end of life products, and production scrap

- Plant capacity 1.4 t per day
  5 days, 50 weeks: 350 t per year
- First Solar`s recycling capacity is high compared to the estimated waste stream
- Production scrap is easily covered by the current capacity

First Solar.



# First Solar



First Solar.

# Summary

The life cycle of First Solar´s products is designed as a closed loop

First Solar provides a module reclamation program

First Solar operates a functioning pilot recycling facility

First Solar recycles more than 95 % in weight of the solar modules

The recycling capacity exceeds todays waste volume

Recycling facilities can be duplicated to increase capacity

First Solar.

Neustadt-Aisch Germany

Dimbach, Germany

First Solar.

# Wet Processing and Recycling of Compound Semiconductor Cells

Dr. Lutz B. Giese[1], Karin Weimann[1] & Kristina Loge[2]

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Unter den Eichen 87, D-12205 Berlin, phone: +49-30/ 8104-1433, fax: / 8104-1437
e-mail: lutz.giese@bam.de; www.bam.de
[2] Technical University of Berlin, Environmental Engineering

### *Abstract*

Photovoltaic thin-film technologies such as CdTe and CIS are considered to be very fruitful for the future. There is a high potential for technical progress and cost reduction, and thus to improve EU perspectives of sustainable energy supply. In 2000 14% of PV modules were manufactured using the thin-film technology. It is supposed that thin film cells based on silicon technologies (a-Si, µ-c-Si) as well as those based on CdTe and CIS will have a greater share in the future. Due to these circumstances, the following issues have to be taken into account:

- Growing production and growing waste potential
- Reputation and acceptance
- Environmental compatibility, under the aspects of WEEE and RoHS
- Resource management aspects
- Recycling strategies

According to FVS (ForschungsVerbund Sonnenenergie), the PV market is growing by 30% annually. In 2000, the cumulative production was expected to rise from 1 $GW_{peak}$ up to 7 $GW_{peak}$ from 2000 to 2010. In 2002, 2.2 $GW_{peak}$ were installed world-wide. Woditsch predicted annual production rates of 0.99 $GW_{peak}$, 6.1 $GW_{peak}$ and 38 $GW_{peak}$ for 2010, 2020 and 2030. Assuming these (conservative) data and a life cycle of 25 years, waste quantities world-wide estimated on power-equivalent masses of different module types may reach 4-10 mill. tons/yr. PV modules (production in 2030, recycling in 2055). Thus, in Europe the sense of the upcoming EU directives WEEE and RoHS on electrical and electronic equipment has to be considered.

Renewable Energy technologies such as photovoltaics and their reputation are based on sustainability. To save the environment from risks and detrimental impacts, environmental compatibility of photovoltaic technology is of highest priority. Compared to fossil fuels, there is an even stronger expectation, especially by critics, towards Renewable Energy technologies such as photovoltaics to apply state-of-the-art technology to consider environmental compatibility. Furthermore, sustainability guarantees the best reputation. Best reputation is the first step towards acceptance and then to distribution of the technology. Thus it has to be canvassed how to achieve progress in environmental compatibility in

- manufacturing,
- operation and
- end-of-life-cycle.

Considering the growing stock of PV systems, end-of-life-cycle management will become more and more important. To maintain good reputation, special efforts are needed for recycling thin-film cell types made of CdTe and CIS. Reaching the end-of-life-cycle, hazardous substances such as cadmium used in CdTe modules may threaten the environment if modules are not recycled properly or are disposed of. Cadmium is known as an toxic, carcinogenic and also teratogenic heavy metal. These facts have to be taken into account in the processing methods, too. Leaching with acids bears the risks of emission of hazardous substances (e.g. $Cd^{2+}$, $H_2Te$, $H_2Se$).

Further development of thin film technologies is impaired by a sustainable availability of resources, as well. Limited elements such as tellurium and indium are needed for CdTe and CIS. For instance, in CIS modules indium shares approx. 0.02 % by weight (Shell ST10: 0.4 g per module, 40 g/$kW_{peak}$). In view of the annual production rates mentioned above and to satisfy the demand on photovoltaic modules by 100% CIS (CdTe),

- in 2010, 40 tons of In/yr. (190 tons/yr. of Te) and
- in 2030, up to 1500 tons of In/yr. (7400 tons/yr. of Te)

will be needed (current technology). On the other hand, resources are limited.

Even if only a part of the future market will be shared by CdTe and/or CIS, both (i) new resources and (ii) recycling will be needed. Whereas there is a sufficient number of technologies for wafer recycling, suitable concepts for thin-film cell treatment are lacking. Thus, industry started research on how to process CdTe and CIS thin film modules, e.g. by leaching with sulphuric or nitric acid and regeneration of the metals and tellurium afterwards by precipitation or electrolysis. However, mostly chemical treatment is necessary, while environmental compatibility is a problem. Innovative concepts for an environmentally compatible recycling are required. Such techniques have to be analysed in view of environmental risk prevention, the requirements resulting from the reputation, and availability of resources.

In 2002, BAM conducted studies on the abilities (i) how to monitor large-scale electronic waste streams and (ii) how to recycle photovoltaic thin-film modules (CdTe and CIS technology) by wet mechanical processing. It is assumed that environmental compatibility can be improved by processing applying existing wet-mechanical technology. The innovative concept consists of a combination of four main processing steps (dismantling, sandblasting, removal of sandblasting agent and refining of cuttings) and avoids using acids and high energy consumption (after dismantling the modules and separating the photo-semiconductors from the carrier by sandblasting).

Environmentally friendly technologies such as photovoltaics have to observe strictly the rules of sustainability to meet requirements by public opinion and environmental compatibility. Whereas until the middle of the 21$^{st}$ century the expected waste quantity from photovoltaics may not reach today's quantities of main waste material currents, nevertheless the development of the market and expected waste quantities should be investigated carefully. Recycling must be aimed at preventing environmental risks and furthermore resource shortages. Taking this into account, disposal and downcycling strategies have to be rejected. Real aim to achieve should be material recycling within an integrated recycling. The processes applied to recycle the modules have to be evaluated carefully in order to assess the ecological effects. Nevertheless, it has to be taken into account that socio-economic sustainability contains both ecological as well as economical sustainability.

Wet processing is aimed at separating valuable and hazardous materials from peripheral construction units and decontaminating them. It has to be shown that wet processing techniques proposed for photovoltaic CdTe and other thin-film modules bear a high potential to decontaminate and separate such composite materials to enable recycling each fraction environmentally friendly and economically.

BAM

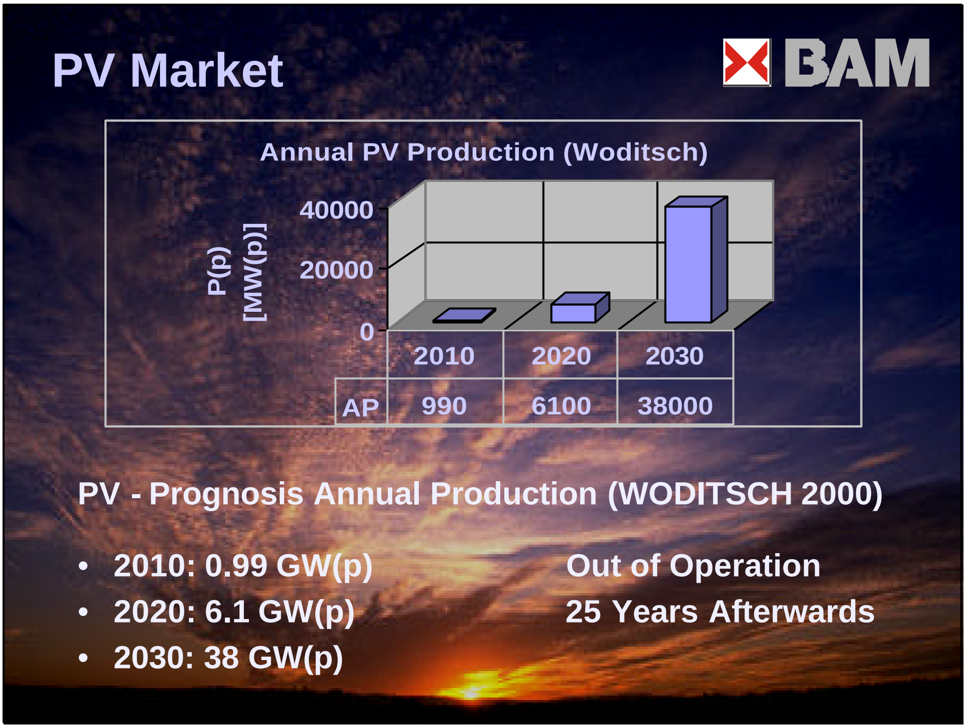
Bundesanstalt für Materialforschung und -prüfung

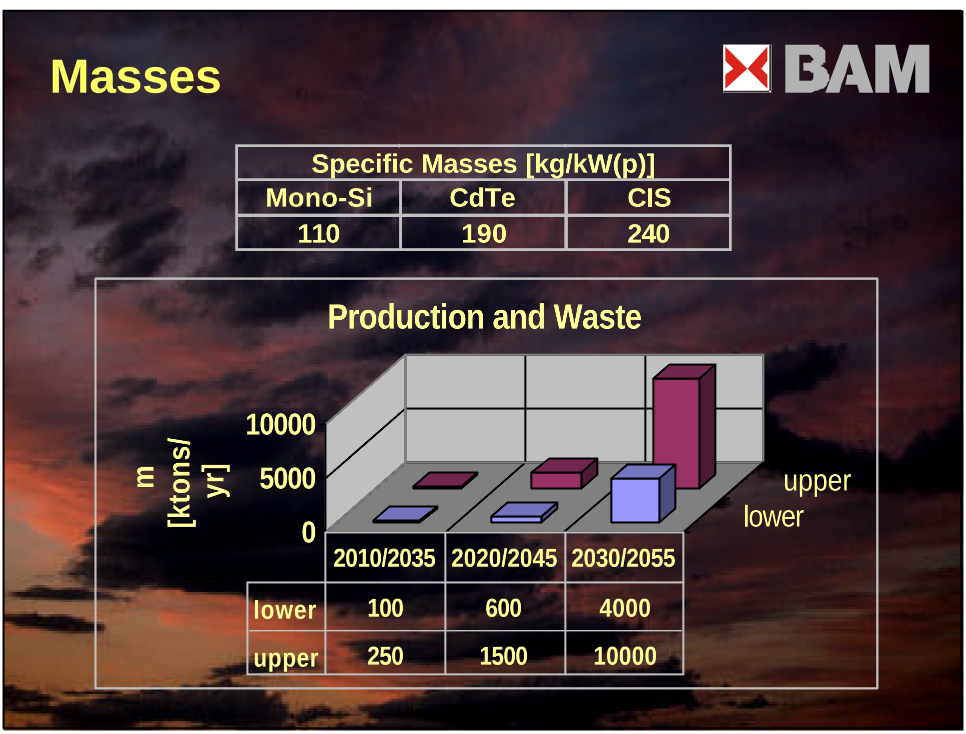
BAM

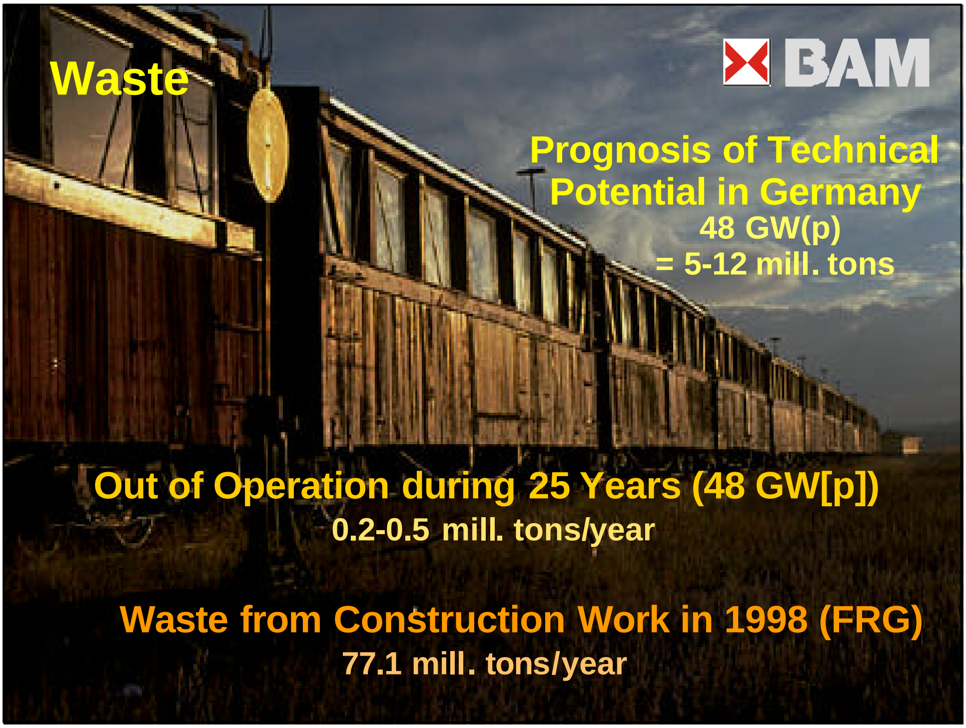
# Wet Processing and Recycling of Compound Semiconductor Cells

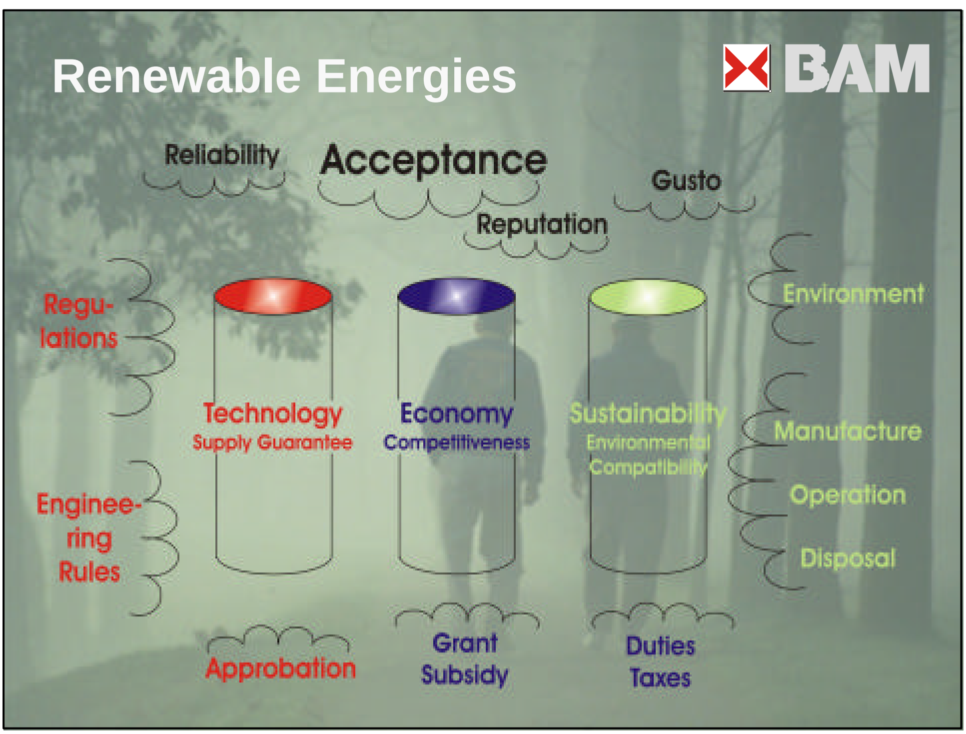

L.B. Giese, K. Weimann & K. Loge

BAM - Federal Institute for Materials Research and Testing
Division IV.3 – Waste Treatment and Remedial Engineering
Germany


PV Market
BAM
Annual PV Production (Woditsch)
P(p)
[MW(p)]
40000
20000
0
2010
2020
2030
AP
990
6100
38000
PV - Prognosis Annual Production (WODITSCH 2000)
• 2010: 0.99 GW(p)
• 2020: 6.1 GW(p)
• 2030: 38 GW(p)
Out of Operation
25 Years Afterwards


Masses
BAM
Specific Masses [kg/kW(p)]
Mono-Si
CdTe
CIS
110
190
240
Production and Waste
m
[ktons/
yr]
10000
5000
0
upper
lower
2010/2035
2020/2045
2030/2055
lower
100
600
4000
upper
250
1500
10000


Waste
BAM
Prognosis of Technical Potential in Germany
48 GW(p)
= 5-12 mill. tons
Out of Operation during 25 Years (48 GW[p])
0.2-0.5 mill. tons/year
Waste from Construction Work in 1998 (FRG)
77.1 mill. tons/year


Renewable Energies
BAM
Reliability
Acceptance
Gusto
Reputation
Regu-lations
Enginee-ring Rules
Technology
Supply Guarantee
Economy
Competitiveness
Sustainability
Environmental Compatibility
Environment
Manufacture
Operation
Disposal
Approbation
Grant
Subsidy
Duties
Taxes

# Sustainability

BAM

Acceptance

Reliability

Reputation

Gusto

Manufacture - Operation - Disposal

- Minimising Energy Input
- Maximising Efficiency
- Emission Prevention
- Disposal Prevention
- Material Recycling
- Resource Protection

Sustainability
Environmental Compatibility

Environment

Manufacture

Operation

Disposal

# Resources

BAM

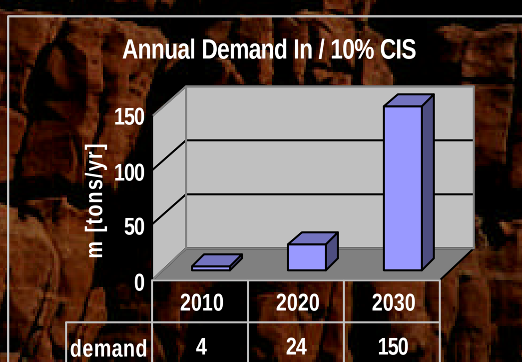
## e.g. CIS Thin-Film Modules

**Copper Indium (Gallium) Selenium Sulphur**

## Indium

- **Annual Production***
  **295 tons/yr**
- **Reserve/Res. Base***
  **2500/6000 tons**
- **Demand per kW(p)**
  **40 g/kW(p)**

***USGS 2004, data: 2003**



## Environment

BAM

### e.g. CdTe Thin-Film Modules

Cadmium Tellurium (Insoluble Solid)

**Pollutant Cadmium**

| Upper Limit | Content | |
|---|---|---|
| LAGA Z.2 | per P(p) | per Mass |
| 10 mg/kg DS* | 170 g/kW(p) | 900 mg/kg |

*(Refill Building Rubble, to Compare)

## Processing and Recycling

BAM

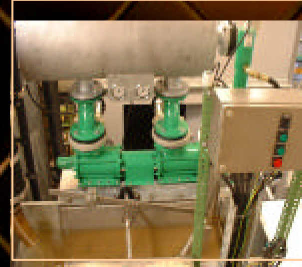
### PV Thin-Film Modules - Low Energy and Additives

Step 1: Module Dismantling, Separation of the Photo Cell/Carrier, Recycling of Valuable Materials

Step 2: Separation of the Thin Film from the Carrier (Sandblasting), Recycling of the Carrier

Step 3: Wet Mechanical Separation of Abrasive and Cuttings

Step 4: Wet Mechanical Separation of the Semiconductor and Recycling



# Conclusions

BAM

**Demonstration of Wet Processing Procedure**
**Reducing Chemical and Thermal Measures**

**Advantage:** Environmental Compatibility, Low Consumption of Energy and Chemical Agents

**Necessity:** Protection of Resources and Environment

**Reputation:** Principle of Sustainability

**Aim:** Integrative Approach
Avoiding Downcycling

---

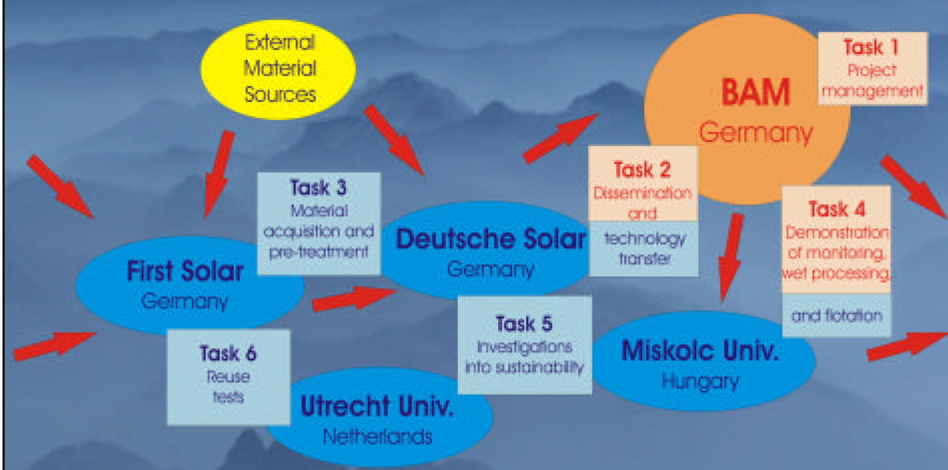
BAM

# Thank You!

lutz.giese@bam.de

# RESOLVED Proposal

***Re**covery of **Sol**ar **V**aluable Materials, **E**nrichment and **D**econtamination*



# PV Module Recycling in the US

Ken Zweibel

NREL
ken_zweibel@nrel.gov, 303 384 6441

### *Not Much Being Done*

Except for general requirements such as RCRA (hazardous waste definitions), no Federal actions

Some states have regulations that might go beyond RCRA

- California (CA) has other limits for hazardous materials
- North Carolina and perhaps CA have recycling programs for items with cathode ray tube

Generally, few PV companies have any policies, with a notable exception (First Solar) and some awareness of Pb issues

### *Reasons*

- Small volume of product.
- Even smaller volume of waste (given long outdoor life of modules, which postpones disposal).
- Tiny amounts of problematic materials (lead solder, and some specialty elements in newer, barely commercial technologies like selenium, cadmium)

### *Compare to Energy Industry*

- PV offsets other sources of energy that themselves cause pollution – implied credit?
- PV is not a classic 'throw away' consumer item.
- PV does not consume electricity, it *produces* it.
- Shouldn't PV products be compared to energy industry products (not consumer items)?

### *New Industry*

New industry with much potential value; needs time to get established before regulations make a deep impact on key technical choices.

- What if short-term priorities kill off the best, new choice(s) before they get started?
- How sure are we that we have the proper balance of good/bad in our valuations – e.g., does CdTe get a *credit* for sequestering waste Cd from zinc mining? How about improved energy-payback for thin films?
- At worst, innovative PV module technologies can increase competition, lowering cost

Plenty of time (30 years) to make the right decision before waste stream becomes large, due to long outdoor life of modules.

### *Some Actions*

Thin film companies in $CuInSe_2$ and CdTe keep track of key regulations.

- Aim is to pass TCLP and similar tests.

First Solar has an extensive program in ES&H of CdTe modules.

- Method of separating materials in waste modules from production.
- 'Take back' plan for old/end-of-life modules.
- Recycling of separated materials.
- Close monitoring of manufacturing safety.

Brookhaven and NREL (DOE) have carried out key studies.

- All aspects of PV ES&H, with emphasis on cadmium, selenium, toxic gases.
- Extensive work on recycling methods and collection procedures.
- "Cadmium Issues in PV" website (http://www.nrel.gov/cdte/).
- Encourage companies to proactively resolve issues.

### *Longer Term Perspective*

If $CuInSe_2$ and CdTe become highly successful, aim at thinner layers to keep the amounts of material small.

- Densities of Cd and Se around 3 g/cm$^3$ imply 3 g/micron-m$^2$; @ 10% efficiency and 1 micron thickness, that's 30 MT/GW.

Layer thicknesses could drop another tenfold to twentyfold (to 0.2 microns) and still absorb 90% of the sunlight.

- Hard challenges to keep efficiencies and production yield high while making layers ultra-thin (may take 15 years to develop this option).
- 0.2 micron layers imply about 6 MT/GW.

Due to limited global tellurium and indium supplies, aggregate amounts for cadmium and selenium in CdTe and $CuInSe_2$ must remain small by historical standards (about 2000 MT/yr maximum) even at 100s of GW per year module production – *doesn't this mean the reward far outweighs the risk?*

- Compare to current *20,000* MT/yr use of cadmium – for toys.

### *Conclusion*

Our goal should be to smartly facilitate the use of PV modules, including proper recycling when the industry reaches a more stable, mature level – and always avoid imposing technology choices prior to proper knowledge of trade-offs and potentials.

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Energy Efficiency and Renewable Energy

# PV Module Recycling in the US

Ken Zweibel
NREL
March 2004

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U.S. Department of Energy
Energy Efficiency and Renewable Energy

## Not Much Actual Recycling Being Done

- Except for general requirements such as RCRA (hazardous waste definitions), no Federal actions
- Some states have regulations that might go beyond RCRA
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  - North Carolina and perhaps CA have recycling programs for items with cathode ray tube
- Generally, few PV companies have any policies, with a notable exception (First Solar) and some awareness of Pb-solder issues by traditional Si companies

# Reasons

- Small volume of product
- Even smaller volume of waste (given long outdoor life of modules, which postpones disposal)
- Tiny amounts of problematic materials (lead solder, and some specialty elements in newer, barely commercial technologies like selenium, cadmium)

U.S. Department of Energy
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# Some Actions

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  - Aim is to pass TCLP and similar tests
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  - Method of separating materials in waste modules from production
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  - Extensive work on recycling methods and collection procedures
  - "Cadmium Issues in PV" website (http://www.nrel.gov/cdte/)
  - Encourage companies to proactively resolve issues

# BNL Research on Recycling

**Vasilis Fthenakis**
**Brookhaven National Laboratory**

- **Collection Infrastructure**
- **Technical Feasibility**

U.S. Department of Energy
Energy Efficiency and Renewable Energy

# Recycling in Other Industries

**Electronics & Telephones**

Used products collected & shipped by 'reverse logistics" contractors
They are shipped as products, not as waste to service center
Usable components salvaged & precious metals reclaimed.
Only units/pieces sent for reclaiming are 'waste"

**NiCd Batteries**

Industry collectively collects and recycles spent NiCd batteries in the US and Canada, via the Rechargeable Battery Recycling Corporation (RBRC).
Batteries are sent to INMETCO, which recovers Ni, Fe and Cd.

# Collection Infrastructure Paradigms

End-user responsible for collection and transport to recycler.

Recyling by dedicated facilities, e.g., smelters

Costs imbedded in the utility rates

Manufacturers individually responsible for collection and recycling.

Collection & transport via reverse logistics companies
Recycling in-house or by dedicated facilities
Costs paid by generator or manufacturer via escrow

Manufacturers collectively responsible for collection and recycling .

Collection & transport via reverse logistics companies
Recycling by dedicated facilities
Costs paid by industry dues to collective recycling entity

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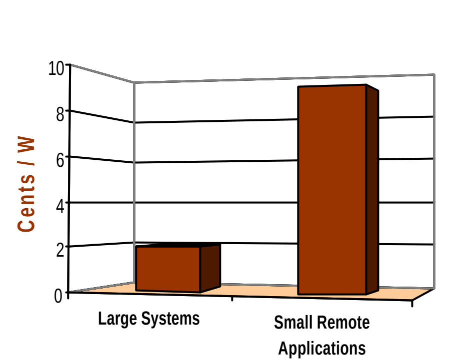
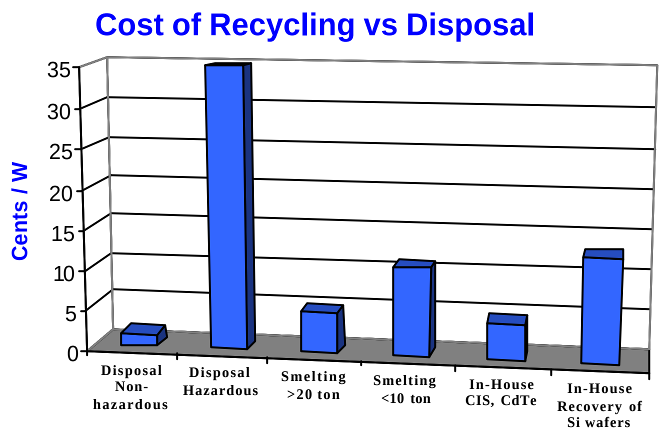
# PV Module Collection & Transportation Costs
($1998 preliminary estimates)



# Total PV Recycling Cost

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# Leaching of Cd from CdTe PV Modules

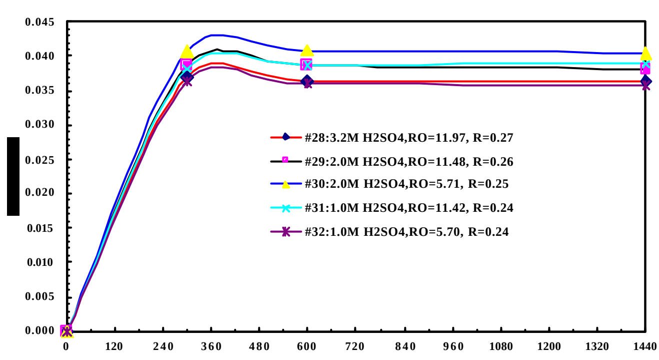


**Figure 8. Cd Leaching Experiments #28,#29,#30,#31,#32. RO-ratio of $H_2O_2$ to glass(mL/kg); R-ratio of leaching solution to glass(kg/kg)**

# Leaching of Te from CdTe PV Modules

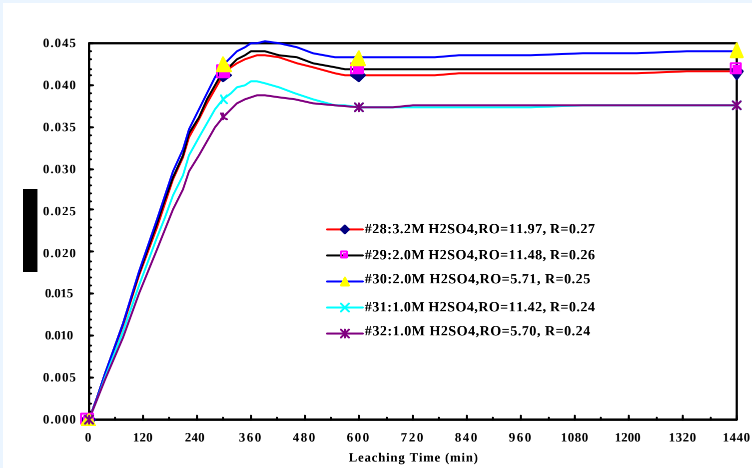


**Figure 9. Te Leaching Experiments #28,#29,#30,#31,#32. RO-ratio of $H_2O_2$ to glass(mL/kg); R-ratio of leaching solution to glass (kg/kg)**

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# Preliminary Results & Ongoing Research

- Cd and Te can be effectively leached from fragments of PV modules with a <u>dilute</u> solution of H2SO4 and H2O2; this can be re-used with a small amount of H2O2 make-up
- Using a dilute solution has cost-, safety and waste-management advantages over currently used solutions
- Preliminary results of separating Cd from Te in solution show a 99.86 to 99.99% separation

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# Uniqueness of CdTe and $CuInSe_2$

- Despite presence of Cd and Se, *crucial* PV thin film options
- Demonstrated highest efficiencies for thin films (11% and 13% at module levels, 16.5% and 19% at cells levels, respectively)
- Best potential for ambitious combination of high module efficiency and very low module costs – combining for dollar/W module potential of under 50 ¢/W, as fully developed and manufactured in volume
- These are unique technologies that cannot be replaced by those without Cd or Se (which is in the absorber, the key element of each technology)

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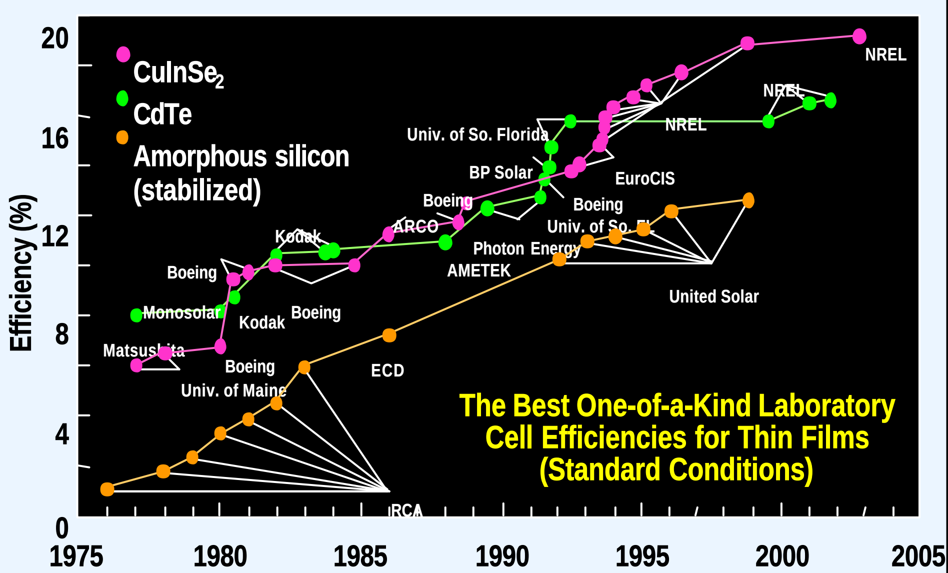

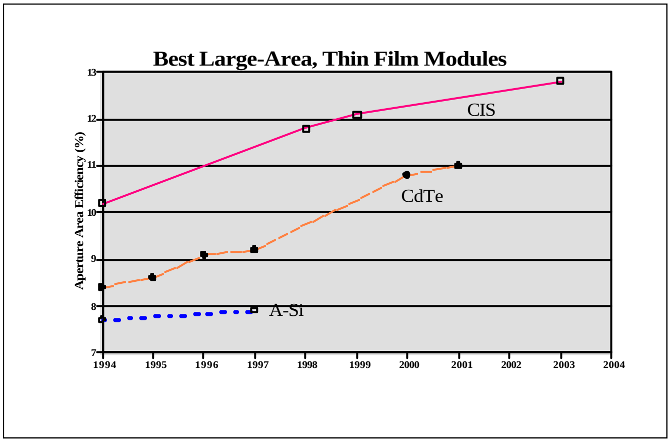


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Energy Efficiency and Renewable Energy

*First Solar Advanced Thin-Film PV Modules at the Tucson Electric Power Array in Arizona.*

# Shell Solar CIS Salzburg and Camarillo



# Longer Term Perspective

- If $CuInSe_2$ and CdTe become highly successful, aim at thinner layers to keep the amounts of material small
  - Densities of Cd and Se around 3 g/cm$^3$ imply 3 g/micron-m$^2$; @ 10% efficiency and 1 micron thickness, that's 30 MT/GW
- Layer thicknesses could drop another tenfold to twentyfold (to 0.2 microns) and still absorb 90% of the sunlight
  - Hard challenges to keep efficiencies and production yield high while making layers ultra-thin (may take 15 years to develop this option)
  - 0.2 micron layers imply about 6 MT/GW
- Due to limited global tellurium and indium supplies, aggregate amounts for cadmium and selenium in CdTe and $CuInSe_2$ must remain small by historical standards (about 2000 MT/yr maximum) even at 100s of GW per year module production – *doesn't this mean the reward far outweighs the risk?*
  - Compare to current *20,000* MT/yr use of cadmium – for toys
- **Our goal should be to smartly facilitate the use of PV modules, including proper recycling when the industry reaches a more stable, mature level – and always avoid imposing technology choices prior to proper knowledge of tradeoffs and potentials**
  - **The risks of reducing PV module competition and reducing long-term cost viability of PV for energy significance would be otherwise too great**

# PV recycling project in Japan

Koichi Sakuta

National Institute of Advanced Industrial Science and Technology (AIST), Japan

As a part of the five year (2001 - 2005) national PV R&D programme funded by the Ministry of Economy, Trade and Industry(METI), the New Energy and Industrial Technology Organization (NEDO) has initiated the R&D project for recycle and reuse of PV systems in 2001, which contains the following research subjects:

- Investigation for Social Systems related to PV recycling
- Recycling and Reuse Technology of c-Si PV Modules
- Recycling and Reuse Technology of CIS Thin Film PV Modules
- Recycling and Reuse Technology of Glass for PV Modules

The objectives of this project is to achieve low recycling cost and high recycling indices about the same as in case of existing products like home electric appliances and automobiles. Proposals of the guidelines for recycling and reuse of PV systems are also expected as the result of this project.

The flow diagram of the PV module recycling and the outlines of each research subjects are shown in the Figures below.

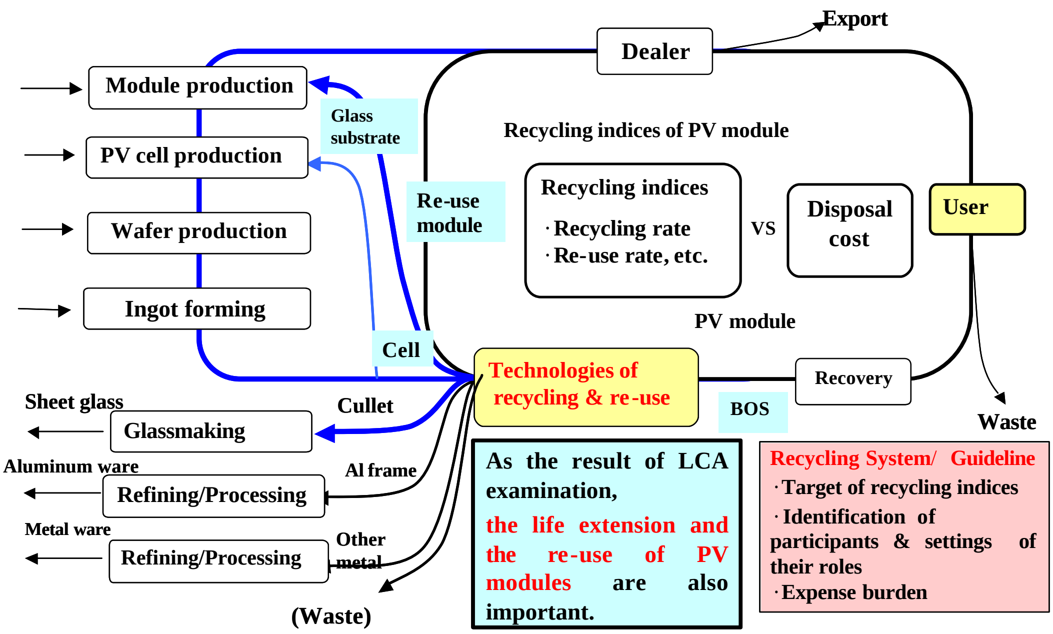


Figure 1: Flow diagram of PV module recycling

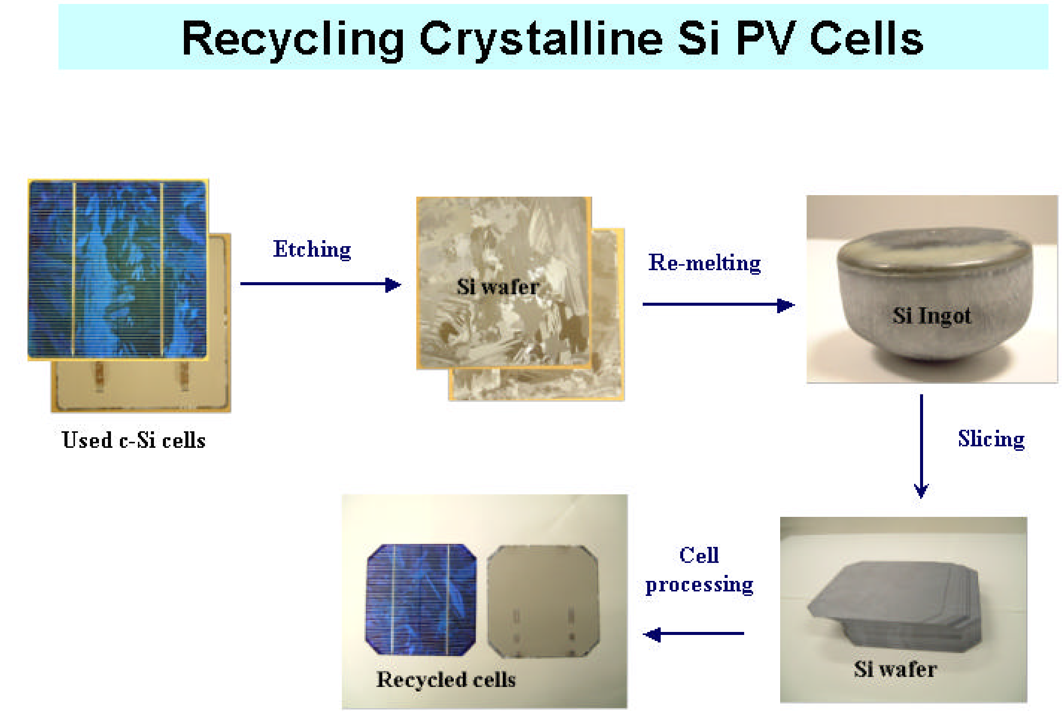


Figure 2: Recycling crystalline silicon PV cells

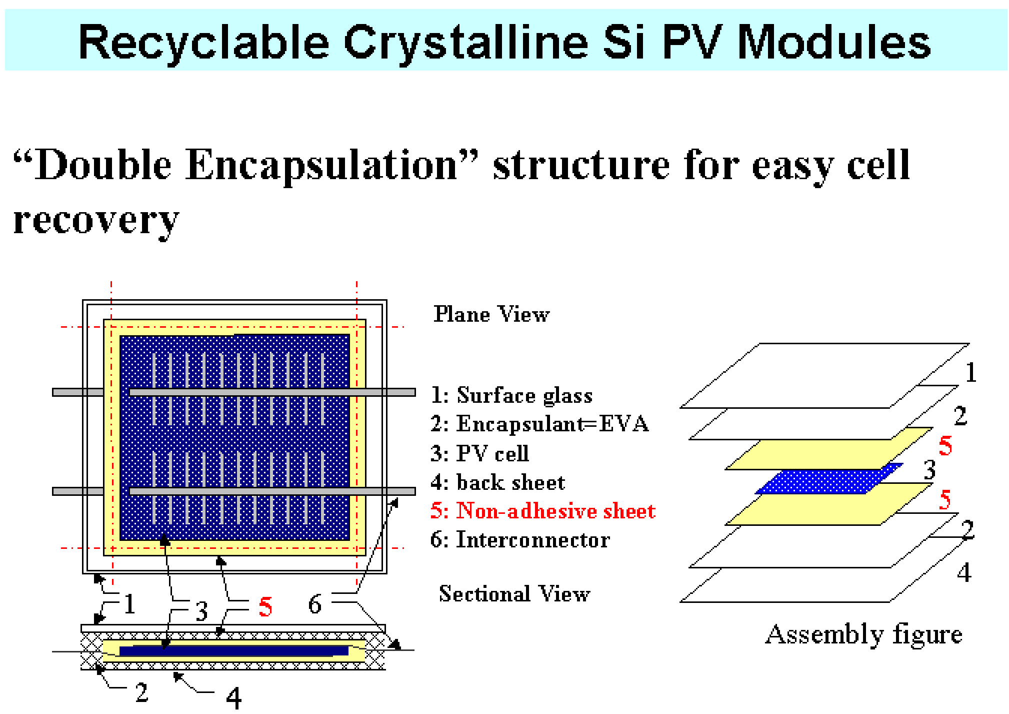


Figure 3: Recyclable crystalline silicon PV modules

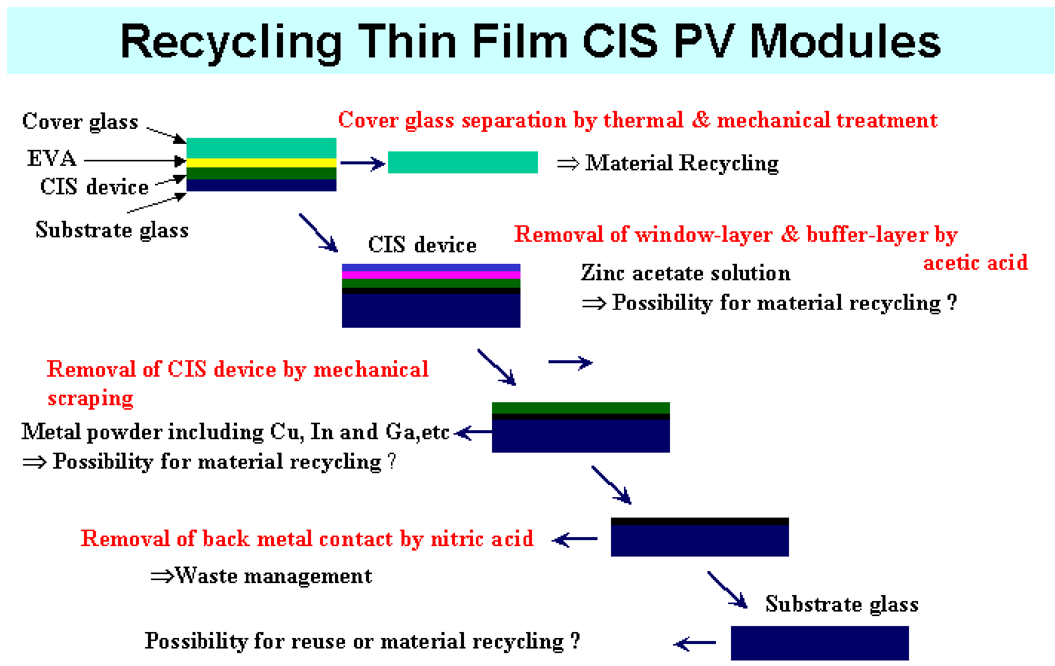


Figure 4: Recycling thin-film CIS PV modules

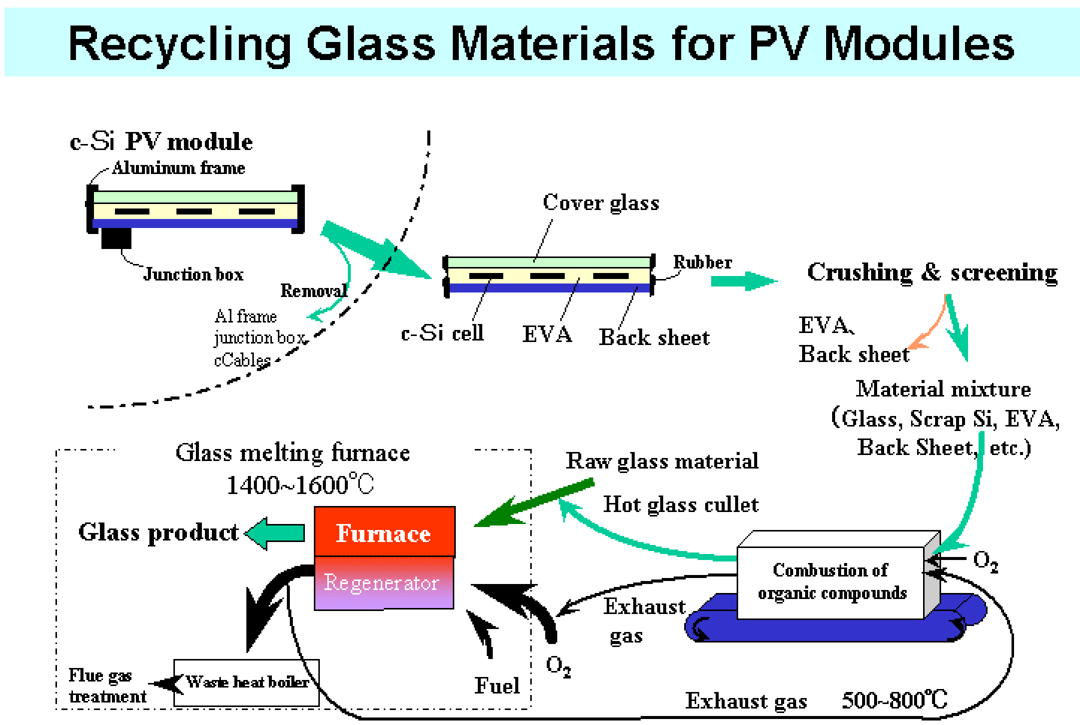


Figure 5: Recycling glass materials for PV modules

# EU Waste Directives and their Consequences for Photovoltaics

## Excerpt on Legislation on Hazardous Substances[9]

Arnulf Jäger-Waldau

European Commission, DG JRC,
Institute for Environment and Sustainability, Renewable Energies Unit

### *Policy considerations*

In line with the Communication on the review of the Community strategy for waste management from 1996, the Proposal for a Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment provides for the reduction of the content of certain hazardous materials in WEEE, including lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) and polybrominated diphenylethers (PBDEs). In this respect, the Proposal follows the principles of existing Community waste legislation, which already included restrictions on the marketing of hazardous substances.

Examples can be found in the European Parliament and Council Directive 94/62/EC on packaging and packaging waste[10] and the Council Directive 91/157/EEC on batteries and accumulators containing certain dangerous substances as amended by Commission Directive 98/101/EC adapting to technical progress Directive 91/157/EEC[11].

Various health and environmental problems linked to the current management of WEEE could be reduced by means of a diversion of these wastes away from landfills and incinerators. This could be achieved by setting up separate collection, treatment and recovery schemes for WEEE. However, at this stage it is unclear when collection rates can be achieved, which represent a substantial part of electrical and electronic equipment put on the market. In the meanwhile, in particular small WEEE will continue to be found in the current disposal routes. In addition, even if WEEE were collected separately and submitted to recycling processes, their content of hazardous substances, poses risks to the health or the environment.

Therefore, the substitution of those substances, which are most problematic in the waste management phase, is the most effective way of ensuring a significant reduction of risks to the health and the environment related to these substances. However, where substitution is not feasible due to the lack of suitable alternatives, exemptions from the requirement to substitute should be granted. These exemptions should be listed in an Annex to the Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment and should be regularly amended in the light of technical progress and new scientific evidence.

The strategy of substituting substances is based on the most current scientific knowledge, taking in particular account of the specific problems caused by these substances in the waste

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9 Proposal for the European Directive 202/95/EC on the restriction of the use of certain hazardous substances in electrical and electronic equipment; COM(2000) 347 final; 13.6.2000

10 OJ L 365, 31.12.1994, p. 10.

11 OJ L 1, 5.1.1999, p. 1.

stream. These substances are well known and have already been subject to a range of different control measures both at Community and national level. However, scientific work on these substances is ongoing and in particular comprehensive risk assessments under Regulation (EC) 793/93 are currently under way for cadmium and three types of PBDE. Although the information emerging to date from these risk assessments gives no reason to believe that the measures foreseen in this Proposal are disproportionate, the scientific work and other work will be kept under review and if necessary this Proposal will be adjusted in accordance with the conclusions of this work.

## *Risks posed by the targeted substances*

### *Lead*

Lead can damage both the central and peripheral nervous systems of humans. Effects on the endocrine system have also been observed. In addition, lead can adversely affect the cardiovascular system and the kidneys. Lead accumulates in the environment and has high acute and chronic toxic effects on plants, animals and micro-organisms[12]. Under Council Directive 67/548/EEC on the classification and labeling of dangerous substances, as amended[13], lead compounds are classified:

- R20/22 Harmful by inhalation and if swallowed,
- R33 Danger of cumulative effects.

The relative importance of any single source of exposure is difficult to predict and will vary with geographic location, climate and local geochemistry. In any case, consumer electronics constitute 40% of lead found in landfills. The main concern in regard to the presence of lead in landfills is the potential for the lead to leach and contaminate drinking water supplies.

### *Cadmium*

Cadmium compounds are classified as toxic with a possible risk of irreversible effects on human health. Cadmium and cadmium compounds accumulate in the human body, in particular in the kidneys which in time may lead to damage. Cadmium is adsorbed by respiration but is also taken up with food. Due to its long half-life (30 years), cadmium can easily be accumulated in amounts that cause symptoms of poisoning. With prolonged exposure cadmium chloride may cause cancer. Cadmium shows a danger of cumulative effects in the environment due to its acute and chronic toxicity[14].

Under Council Directive 67/548/EEC on the classification and labeling of dangerous substances cadmium compounds are classified:

- R23/25 Toxic by inhalation, if swallowed.
- R33 Danger of cumulative effects.

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12 Compare Risk Reduction Monograph No 1 Lead – Background and national experience with reducing risk, OECD Paris 1993.

13 OJ L 196, 16.8.1967, p. 1.

14 This information is based on the risk reduction monograph no 5, CADMIUM, Background and national experience with reducing risk (OCDE/GD894) 97; Health effects of cadmium exposure-a review of the literature and a risk estimate (Lars Järup and others) Scand J. Work Environ Health 98; Environmental impacts of cadmium, Gerrit H. Vonkeman 1995; Cadmium in Sweden-environmental risks, Helena Parkman and others 1997 and other research on this issue.

- R40 Possible risks of irreversible effects.

### *Mercury*

Inorganic mercury spread in the water is transformed to methylated mercury in the bottom sediments. Methylated mercury is easily accumulated in living organisms and concentrates through the food chain via fish. Methylated mercury has chronic effects and causes damage to the brain.

Under Council Directive 67/548/EEC on the classification and labeling of dangerous substances, as amended, mercury is classified:

- R23/24/25 Toxic by inhalation, in contact with skin and if swallowed.
- R33 Danger of cumulative effects.

Under Council Directive 67/548/EEC on the classification and labelling of dangerous substances, as amended, mercury alkyls and inorganic compounds of mercury are classified:

- R26/27/28 Very toxic by inhalation, in contact with skin and if swallowed.
- R33 Danger of cumulative effects.

It is estimated that 22% of annual world consumption of mercury is used in electrical and electronic equipment.

### *Hexavalent chromium (Chromium VI)*

Chromium VI can easily pass through cell membranes. Accordingly, chromium VI is easily absorbed and produces various toxic effects within the cells. Therefore, chromium VI is considered an important risk for the environment in industrialised countries. Furthermore, chromium VI causes severe allergic reactions. Small concentrations of chromium VI in the environment might lead to an increase of allergies. Asthmatic bronchitis is another allergic reaction linked to chromium VI. Chromium VI is also considered genotoxic, potentially damaging the DNA.

In addition, hexavalent chromium compounds are assumed to be toxic for the environment.

As regards possible exposure, chromium VI contained in wastes can easily leach from landfills which are not appropriately sealed. During incineration of chromium VI contaminated wastes the metal evaporates through fly ash. Chromium VI in the fly ash is easily soluble. There is agreement among scientists that wastes containing chromium should not be incinerated.

### *Brominated flame retardants*

Brominated flame retardants are regularly designed into electronic products today as a means of ensuring flammability protection. The use is mainly in four applications: in printed circuit boards, components such as connectors, plastic covers and cables. 5-, 8- and 10-BDE are mainly used in printed circuit boards, plastic covers of TV sets and domestic kitchen appliances.

One of the main objectives of the present Proposal is to divert WEEE from disposal operations and to increase recycling of this waste. This is in particular true for plastics, which constitutes 20% of the composition of WEEE. One of the main impediments to the recycling of this fraction is the risk of dioxin and furan generation by certain brominated flame retardants during the recycling of the respective plastic. In particular, it has been shown that polybrominated diphenylethers (PBDEs) formed the toxic polybrominated disbenso furans (PBDF) and polybrominated disbenso dioxins (PBDD) during extrusion, which is part of the plastic recycling process. As a consequence, the German chemical industry stopped the production of these chemicals in 1986[15].

In addition, high concentrations of PBDEs have been found in the blood of workers in recycling plants[16]. Various scientific observations indicate that PBDEs might act as endocrine disrupters.

The presence of polybrominated biphenyls (PBBs) in Arctic seal samples indicates a wide geographical distribution. The principal known routes of PBBs from point sources into the aquatic environment are PBBs plant areas and waste dumps. PBBs are almost insoluble in water and are primarily found in sediments of polluted lakes and rivers. PBBs have been found to be 200 times more soluble in landfill leachate than in distilled water. This may result in a wider distribution in the environment. Once PBBs have been released into the environment, they can reach the food chain, where they are concentrated. PBBs have been detected in fish from several regions. Ingestion of fish is a source of PBB transfer to mammals and birds. Neither uptake nor degradation of PBBs by plants has been recorded. In contrast, PBBs are easily absorbed by animals and although they have been found to be very persistent in animals, small amounts of PBB metabolites have been detected[17].

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15 See "Formation of Polybrominated Dibenzofurans (PBDF's) and –Dioxins (PBDD's) during extrusion production of a Polybutyleneterephtalate (PBTP)/ Glassfibre resin blended with Decabromodiphenylether (DBDPE)/Sb2O3; product and workplace analysis" Brenner, Knies, BASF 1986. Further information to be found in "Polybrominated Diphenyl Ethers in the Swedish Environment", Ulla Sellström, Stockholm 1996.

16 Flame retardant exposure – Polybrominated diphenyl ethers (PBDEs) in blood from Swedish workers, Sjödin et al. Stockhom 1999.

17 Information and recommendation from the risk reduction monograph no 3, selected brominated flame retardants – Background and national experience with reducing risk, OECD Paris 1994.

# EU Waste Directives and their Consequences for Photovoltaics

**Arnulf Jäger-Waldau**







# Background

European Directives 2002/96/EC and 2002/95/EC (**27 January 2003)**
- on waste electrical and electronic equipment (WEEE)
- on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS)

have to be implemented by the Member States by 13 August 2004 !

⇒ PV is not included in the technical Annex yet,
but it is explicitly mentioned in Article 13 of WEEE

# ANNEX IA of WEEE

**Categories of electrical and electronic equipment covered by this Directive**

1. Large household appliances
2. Small household appliances
3. IT and telecommunications equipment
4. Consumer equipment
5. Lighting equipment
6. Electrical and electronic tools (with the exception of large-scale stationary industrial tools)
7. Toys, leisure and sports equipment
8. Medical devices (with the exception of all implanted and infected products)
9. Monitoring and control instruments
10. Automatic dispensers



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# WEEE Article 13

**Adaptation to scientific and technical progress**

Any amendments which are necessary in order to adapt Article 7(3), Annex IB, (in particular with a view to possibly adding luminaires in households, filament bulbs and **photovoltaic products, i.e. solar panels**),

Annex II (in particular taking into account new technical developments for the treatment of WEEE), and Annexes III and IV to scientific and technical progress shall be adopted in accordance with the procedure referred to in Article 14(2).

Before the Annexes are amended the Commission shall *inter alia* consult producers of electrical and electronic equipment, recyclers, treatment operators and environmental organisations and employees' and consumer associations.

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# Directive 2002/95/EC (RoHS)

*Article 2*

**Scope**

1. Without prejudice to Article 6, this Directive shall apply to electrical and electronic equipment falling under the categories 1, 2, 3, 4, 5, 6, 7 and 10 set out in Annex IA to Directive No 2002/96/EC (WEEE) and to electric light bulbs, and luminaires in households.
2. This Directive shall apply without prejudice to Community legislation on safety and health requirements and specific Community waste management legislation.
3. This Directive does not apply to spare parts for the repair, or to the reuse, of electrical and electronic equipment put on the market before 1 July 2006.



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# Excerpt on Legislation on Hazardous Substances

COM(2000) 347 final; 13.6.2000 and RoHS Article 4(1)

***Explicitly mentioned substances and their risks***

***Lead*** (included in solder for PV modules)

***Cadmium*** (absorber material CdTe; buffer CIS)

***Mercury***

***Hexavalent chromium (Chromium VI)***

***Brominated flame retardants***

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# Consultation Activities of DG ENV

Here some updates regarding Directive 2002/95/EC (RoHS):

With regard to Article 5(1)(a)
(establishment of max. concentration values)
- In December last year DG ENV has launched a stakeholders consultation on a draft decision on "maximum concentration values".

The results of the consultation were presented to the Member States at the Technical Adaptation Committee meeting held on 27/01/2004.

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# Consultation Documents

**Proposed limit values, based on existing Community Chemicals legislation and are considered to be the most appropriate to ensure a high level of protection**

**"A maximum concentration value of 0.1% by weight in homogenous materials for:**
**lead, mercury, hexavalent chromium, polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE)**
**and of 0.01% weight in homogenous materials for:**
**cadmium**
**shall be tolerated. Homogenous material means a unit that can not be mechanically disjointed in single materials.**

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# Current activities

RoHS Article 5(1)(b) - In January this year the Commission has published a call for tender for a study covering:

1) Item 10 of the Annex to the RoHS directive
(with the exclusion of DecaBDE that is currently being assessed under Regulation 793/93/EEC)

2) Additional exemptions
The study is due to be completed in 5 months from the award of the contract (the award is expected in April).
Results expected by October 2004

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# ANNEX of RoHS

**Applications of lead, mercury, cadmium and hexavalent chromium, which are exempted from the requirements of Article 4(1)**

5. Lead in glass of cathode ray tubes, electronic components and fluorescent tubes.
6. Lead as an alloying element in steel containing up to 0,35 % lead by weight, aluminium containing up to 0,4 % lead by weight and as a copper alloy containing up to 4 % lead by weight.
7. - Lead in high melting temperature type solders (i.e. tin-lead solder alloys containing more than 85 % lead),
   - lead in solders for servers, storage and storage array systems (exemption granted until 2010),
   - lead in solders for network infrastructure equipment for switching, signalling, transmission as well as network management for telecommunication,
   - lead in electronic ceramic parts (e.g. piezoelectronic devices).

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# ANNEX of RoHS

8. Cadmium plating except for applications banned under Directive 91/338/EEC (1) amending Directive 76/769/EEC (2) relating to restrictions on the marketing and use of certain dangerous substances and preparations.
10. Within the procedure referred to in Article 7(2), the Commission shall evaluate the applications for:
    - Deca BDE,
    - mercury in straight fluorescent lamps for special purposes,
    - lead in solders for servers, storage and storage array systems, network infrastructure equipment for switching, signalling, transmission as well as network management for telecommunications (with a view to setting a specific time limit for this exemption), and
    - light bulbs,

as a matter of priority in order to establish as soon as possible whether these items are to be amended accordingly.





# *Article 6:* Review of RoHS

Before 13 February 2005, the Commission shall review the measures provided for in this Directive to take into account, as necessary, new scientific evidence.

In particular the Commission shall, by that date, present proposals for including in the scope of this Directive equipment which falls under categories 8 and 9 set out in Annex IA to Directive 2002/96/EC (WEEE).

The Commission shall also study the need to adapt the list of substances of Article 4(1), on the basis of scientific facts and taking the precautionary principle into account, and present proposals to the European Parliament and Council for such adaptations, if appropriate.

# Regulation Scenarios for Waste PV-Modules

Stéphanie Zangl

Ökopol, Hamburg, Germany

### *Abstract*

Photovoltaic modules (PV-modules) have been installed on a large scale over the past years. The advantages and drawbacks of PV-technology have been widely analysed though leaving out waste management issues. The yearly emergence of PV modules that need to be disposed of reaches the same dimension as the installed capacity with a delay of about 30 years. Therefore the expected generated waste amounts for 2002 was of approximately 290 t, for 2010 it will be of about 1,110 t and for 2040 it is expected to be of 33.5 thousand tons.

Figure 1 shows requirements for the product design and treatment paths for three module types from an environmental point of view.

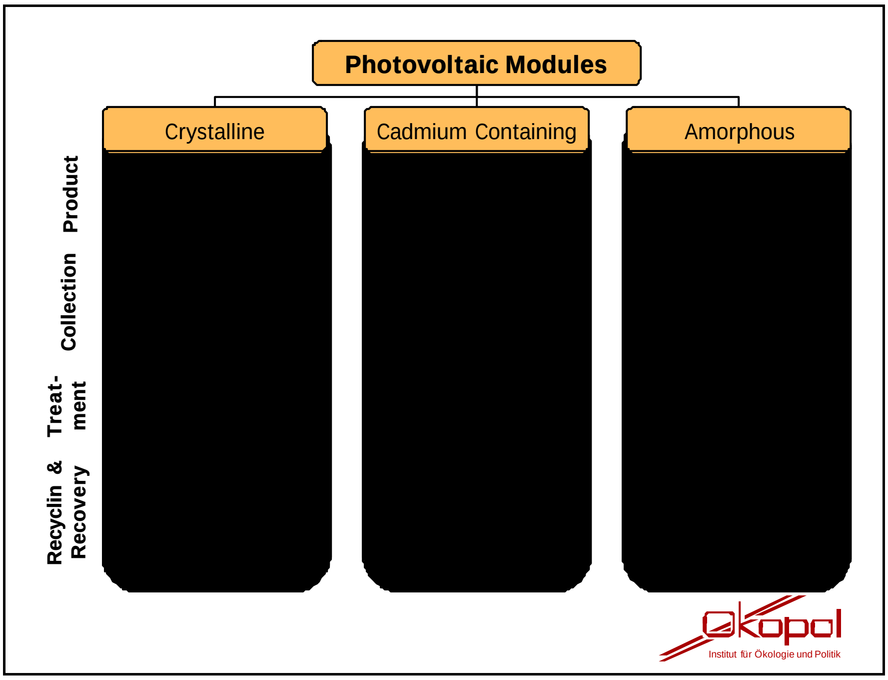



Figure 1: Requirements for treatment paths of PV-modules

With regard to legal framework three approaches are conceivable in order to support the fulfilment of these requirements:

### *1. Incorporation into the scope of the WEEE- and RoHS-Directives*

An incorporation of PV-modules into the scope of the WEEE- and RoHS-Directives should go along with adding CdTe- and CdS-films as well as lead-containing frits to the annex of the

RoHS-Directive (exemptions of use restriction of substances). Substitution possibilities exist for lead-containing solders hence they should not be part of the exemptions. The dismantling obligations should be expanded to cadmium-containing components and tin-plated copper bands. A further extension to the Si-fraction is sensible in order to create the necessary conditions for the recycling of valuable silicon from Si-modules.

The instrument of recycling and recovery rates used in the WEEE-Directive is in general a suitable instrument for the achievement of the environmental goals “separated collection” and “recycling/recovery”. The recycling and recovery rates are achievable due to the high glass and metal content, independently of the category the modules are allocated to. In the first instance the incorporation into the scope of the WEEE- and RoHS-Directives therefore appears able to support reaching environmental and waste policy goals concerning PV-modules.

Nevertheless recovery and recycling rates would only be appropriate to secure the recycling of silicon elements (about 3 % in Si-modules) if the rates refer to the material (here the silicon) rather than to the whole device. For cadmium it appears sensible to introduce a collection-rate.

### *2. National regulation within the framework of German waste law (KrW-/AbfG)*

Most of the PV-module waste will probably occur during commercial operations. Therefore the German ordinance on industrial waste (Gewerbeabfallverordnung - GewAbfV) would be applicable. The German waste law (KrW-/AbfG) contains the requirement for “high grade recovery”, however it is not put into force yet. The German ordinance on industrial waste does not include any target-orientated instruments either. The recovery rate of 85 % included in the ordinance is already reached with any form of glass and metal recovery (i.e. also with the application for backfilling mining areas).

### *3. Commitment by industry*

A self-binding commitment of the industry would allow utilising the economic incentive of silicon-recycling. The necessity to ensure clearly defined, revisable and ambitious goals as well as an efficient monitoring has to be pointed out. Facing the long life-time of the modules and the high dynamic of the market, a fundamental problem of this solution is that some of the producers may not be operating on the market any more at the equipment’s “end-of-life-time”.

Workshop on LCA and Recycling of Solar Modules, Brussels 19 March 2004

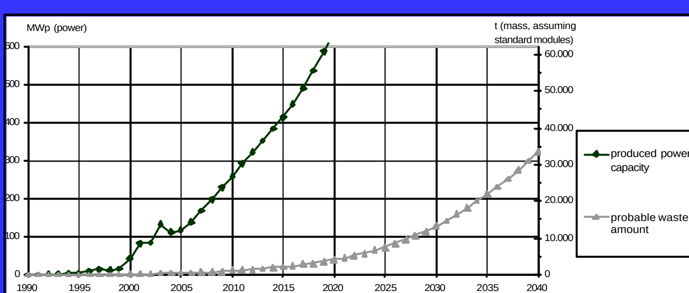
# Regulation Scenarios for Waste PV Modules

**Stéphanie Zangl**

Institute for Environmental Strategies



## Medium-Term Forecast Generated Waste Amounts




Sources: Production until 2003: IEA 2002, KfW (statistical data about 100 000-roofs-programme, UVS, from 2004 on: long term scenarios from UBA, waste amount: Calculations of IE Leipzig

Amount EOL PV Modules same amount as installed capacity with 30 years delay

| | |
|---|---|
| 2002 | 290 t |
| 2010 | 1.110 t |
| 2040 | 33,5 kt |



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# Requirements for EOL PV Modules

- Product (Design for Dismantling)
- Collection (Inception of EOL modules)
- Treatment (Depollution/Dismantling)
- Recycling & Recovery (Waste hierarchy)





## Photovoltaic Modules

| | Crystalline | Cadmium Containing | Amorphous |
|---|---|---|---|
| **Product** | **separability Si; Substitution Pb** | substitution Cd, Pb | reduction Si-amount |
| **Collection** | **preferably complete; separate; not destroyed** | preferably complete; separate; not destroyed | with similar material flows |
| **Treat-ment** | **separation Si, glass, metal, tin-plated copper conductors** | separation Si, glass, metal, tin-plated copper conductors | separation glas, metal |
| **Recyclin & Recovery** | **reuse/recovery Si; recovery of glass, metal** | **extraction of Cd**; recovery of semi-conductors, glass, metal | **recovery glas, metal** |

## Implementation

| Module Type | Process |
|---|---|
| Crystalline | Thermal process of Deutsche Solar AG (currently pilot plant in testing operation); economically profitable |
| Amorphous | Common treatment with similarly composed wastes (e.g. construction waste) |
| Cadmium-containing | No plant available in Europe; Treatment with other Cd-containing material streams |



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## Three Approaches to Legal Framework

- WEEE- & RoHS-Directives
- National Regulation (e.g. German Waste Law)
- Commitment by Industry



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## Incorporation into the WEEE Directive

- Separate Collection (Target 4 kg/Inh*a)
- Treatment Requirements (Annex II & III)
- Recycling & Recovery targets
- Financing obligations (producer responsibility)
- Information & Reporting (Monitoring)





## Scope of the WEEE Directive

- PV modules fall under definition of EEE but are not listed in Annex IA/IB!
- Article 13 (1): Adaptation to scientific and technical progress foresees possible incorporation of PV products (i.e. solar panels) to Annex IB (to be adopted by TAC)

## Time frame

Entry into force — Transposition

| 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|
| 13.02 | | 13.08 / 13.08 | 13.08 | 31.12 | 31.08 | 30.06, 31.12 |

Collection: 4 kg/E*a (31.12.2006); New collection rate (31.12.2008)

Monitoring: Reuse/recycling & recovery rates (31.12.2006); Revision rates (31.12.2008)

Financing



Regulation Scenarios for Waste PV Modules

## Incorporation into RoHS Directive

*Substitution of certain heavy metals and brominated flame retardants where alternatives are available*

- By 1 July 2006, no equipment may be sold containing the concerned substances (except refurbished equipment and specific applications mentioned in the Annex to the Directive)
- Heavy metals: Mercury, lead, cadmium and hexavalent chromium
- Brominated flame retardants: PBBs (polybrominated biphenyls) and PBDEs (polybrominated diphenylethers)

Workshop on LCA and Recycling of Solar Modules, Brussels 19 March 2004

## RoHS Directive – Impact PV Modules

| Element | Contained in |
|---|---|
| Lead | lead-containing frits (lead-containing printing pastes for screen printing on semi-conductors) |
| | Solder |
| | copper-strip connector (solder coating) |
| Mercury | Not contained |
| Cadmium | Semiconductor film:<br>- as CdS (CIS + CdTe modules)<br>- as CdTe (only CdTe modules)) |
| Hexavalent chromium | Not contained |
| Flame retardants | Not contained |



Regulation Scenarios for Waste PV Modules

## National Regulation (e.g. German Waste Law)

- German Waste Law contains requirements for „high grade recovery“ – however not put into operation!
- Most EOL modules occur during commercial operations: German Ordinance on Industrial Waste of application
- General recovery rate of 85% - is already reached with any form of glass and metal recovery

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## Commitment by Industry

- Use existing economic incentive for silicon recycling
- Necessity for clearly defined, revisable and ambitious goals
- Efficient monitoring prerequisite
- High dynamic of the market: some producers might not be operating on the market at „end-of-life-time“ of modules







## Regulation Scenarios

| Legal Framework | Consequences for PV Modules/Recommendations |
|---|---|
| WEEE | Material-based rate<br>Extension dismantling obligations |
| RoHS | Use restrictions<br>Exemptions |
| German Waste Law | Silicon recovery not feasible |
| Commitment Industry | Clear goals and efficient monitoring |

Workshop on LCA and Recycling of Solar Modules, Brussels 19 March 2004

Institute for Environmental Strategies


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# Waste Directives and their impact to the European Photovoltaic Industry

Eleni Despotou

EPIA, Brussels

The European Directives 2002/96/EC on waste electrical and electronic equipment (WEEE) and 2002/95/EC on the restriction of the use of certain hazardous substances in electrical and electronic equipment (ROHS) have to be implemented by the Member States in 2004 and will have a significant impact on the photovoltaic industry.

The European PV industry is rapidly growing during last five years manufacturing and distributing high quality and environmentally friendly products for renewable energy production. PV products are carefully designed for long lifetimes above 25 years, for this reason the amount of end of life modules at present is quite small. Larger quantities are expected around the year 2020.

The ROHS directive restricts the use of several materials, e.g. of lead and cadmium, that may be present in small amounts in PV modules as well. An exceptional grant for such materials in photovoltaic products therefore must be achieved. (Similar exceptional cases are already included for other products containing even bigger quantities of hazardous components.) If PV products will be covered by the WEEE and ROHS directives materials like CdTe and CdS used in compound semiconductor modules and Pb from the frits used in the screen printed metallization of crystalline silicon cells or in solder alloys on the tabs should be included in the appendix of the ROHS directive (exceptions of material restrictions).

However, our Industry is young and needs time to get established before early regulations may provoke deep impact on key technological choices. The industrials are continually working on the improvement of their products in terms of efficiency, cost reduction, new fabrication processes and life time improvement. The costs of waste treatment are generally included in the costs of all components in the value chain but not yet for modules at the end of their life. The costs can be calculated between 0, 10 €/Wp and 0, 40 €/Wp depending on the type of module, transportation, waste treatment and disposal costs ([18]). As the situation is fluctuating it could be very difficult to implement these directives.

The European PV industry has already established voluntarily a running solution for high value recycling of their products that can easily be extended with growing demands and will be improved continuously.

EPIA proposes the following scheme: In a first stage to not include PV modules in the directive. PV production is not widely spread, concentrated in certain geographical areas, the amount of waste from production and installations is very small today. Thanks to the stable and enduring encapsulation of the modules no environmental pollution is expected. End of life modules are industrial waste (Oekopol study), further regulation may be required in some years. In the meantime, the industry will be engaged to adapt their technologies, fabrication processes as well as recycling and reuse possibilities in order to achieve by 2010 the requirements of the

[18] Source: Deutsche Solar

directives. The photovoltaic industry will work together with the authorities to provide necessary data and specify future waste treatment and regulation.

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# *The EU Waste Directives and their Consequences for EU PV Industry – The "Waste" Challenge*



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## EPIA and its members

**EPIA represents 95% of European Photovoltaic Industry, covering the whole chain of production:**

- ***Silicon feedstock:*** Scanwafer, Wacker, Pillar, Elkem…
- ***Wafers and Ingots:*** Crystallox, Deutsche Solar, PV Silicon…
- ***Cells:*** Q-cells, BP Solar, Isofoton, Shell Solar…
- ***Modules:*** RWE Schott Solar, Photowatt, Photovoltech…
- ***Systems:*** Total Energie, Naps Systems, Ersol, AET…
- ***Inverters:*** SMA, Philips

**Eleni Despotou** Brussels, 18 and 19 March 2004

EUROPEAN PHOTOVOLTAIC INDUSTRY ASSOCIATION

# EPIA strategy for the next three years

## *Objectives:*

- ***EPIA*** *will become the* ***most credible*** *reference point for the European PV Industry stakeholders.* ***EPIA*** *will provide* ***accurate information****,* ***statistics*** *and* ***feedback*** *to both its members and the wider audience.*
- ***EPIA*** *will help shape* ***the development*** *of new PV markets both in Europe and export community.*
- ***EPIA*** *will* ***take the lead in positioning*** *the photovoltaic industry within the European political environment* ***and supporting*** *the member state association in their local objectives.*



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# European PV market today represents:

- More than **15.000 jobs**
- 1 billion € 2003 investment
- Market growth **2002-2003: 33%**
- High technology production
- Research and innovation
- Highly qualified employees

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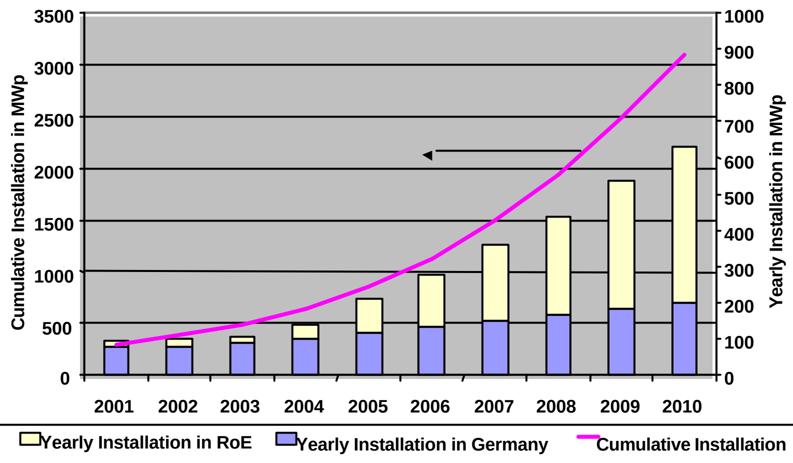
# PV Market Development Projection in Europe



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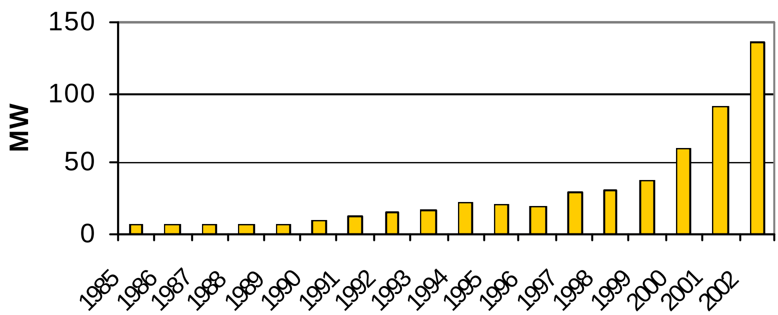
# Europe cell/module Production (MWp)



## However:

- New technology
- Fragile industry
- Need for support
- Sensitive on environmental issues



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## PV modules WEEE and ROHS

- End of life modules are considered as industrial electronic waste in most of cases
- PV industry may set up its own take-back system
- Not absolutely necessary **yet** (life cycle 25-30 years)
- PV modules already included in art. 13 of WEEE.
- Significant for green image of PV industry

Eleni Despotou Brussels, 18 and 19 March 2004

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# Consequenses for PV industry

- New waste classification of products
- Re-use and recycling prior to disposal, recycling quotas
- Central monitoring
- New marking of products
- Set up for collection system
- Transportation and storage limitations
- Long term waste treatment financing (25-30 years), escrow funds



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# EPIA and BSi propose the following proactive scheme setting up a timeframe

- In a first stage **(2004),** they wish that PV products are excluded from the directive,
- Collaborate with the task force in order to provide input on waste and recycling issues,
- **2004 to 2010** volontary recycling of PV products and progressive adaption of industry to the requirements of the directives.

EUROPEAN PHOTOVOLTAIC INDUSTRY ASSOCIATION

## Members of EPIA and BSi are kindly asked to support the following necessary actions:

- Authorize the Associations representing PV industry to negotiate economic solutions with European and national authorities and to set up an international working group
- Ensure discussion and information exchange between ministry departments of RES and waste treatment as well as PV industry
- Negotiate possible timeframe of the integration of EOL-PL in WEEE an its national transposition
- Define waste streams and possible collection systems



EUROPEAN PHOTOVOLTAIC INDUSTRY ASSOCIATION

## Members of EPIA and BSi are kindly asked to support the following necessary actions:

- Ask for exemptions on the use of (small amounts of) hazardous and toxic substances in photovoltaic products
- Cooperate and provide solutions within present and forthcoming European and national regulations in cooperation with politicians and authorities
- Define a Roadmap to establish a middle and long term sustainable waste treatment strategy
- Inform the members prior to forthcoming change in legislation
- Everyone who wishes to join the working group can contact EPIA.

# Thank you for your attention!

**Email:** epia@epia.org

**Web:** www.epia.org

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